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FORT EUSTIS, VIRGINIA

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VTOL AIRCRAFT DOWNWASH IMPINGEMENT SYMPOSIUM

A Compilation of the Papers Presented

15 December 1960

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VTOL AIRCRAFT DOWNWASH IMPINGEMENT SYMPOSIUM

A Compilation of the Papers Presented

at

U. S. Army Transportation Research Command
Fort Eustis, Virginia

15 December 1960

CONTENTS

INTRODUCTION

This publication is a compilation of the technical papers presented at the VTOL Aircraft Downwash Impingement Symposium held at Fort Eustis, Virginia, on December 15, 1960. The primary purpose of the conference was to bring together a cross section of industry and the military services in an effort to alleviate the problem of VTOL aircraft downwash impingement. Downwash not only hampers the operator but, because of dust signature, discloses forward-area positions to hostile forces. Moreover, the difficulties encountered in hooking up and discharging a sling load from a helicopter are compounded by downwash.

It is hoped that this symposium will develop a better understanding of the problem and a fuller appreciation of the urgency of solutions so that winged VTOL aircraft may become useful air vehicles for operation in the Army combat environment. Unless a solution is found, the likelihood exists that some of the machines that the military and industry would like to see built may not be realized because of the magnitude of the operational, tactical, and logistical problems that are evident.

ROSTER

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Ptachick, Robert J.	Goodyear Aircraft Corporation
Rawlings, W. L.	Aeronutronic "A" Division of Ford Motor Company
Robinson, Donald W., Jr.	Kaman Aircraft Corporation
Salmanson, Jay A.	Research & Dev. Operations Army Rocket & Guided Missile Agency
Sargent, Elbert	Hiller Aircraft Corporation
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Sellman, E. W. LCDR	Bureau of Naval Weapons, Washington, D. C.
Simmons, R. L. LCDR	COMNAVAIRLANT Staff Naval Air Sta. Norfolk, Virginia
Smith, Roderick L.	Sikorsky Aircraft
Sohn, Ronald F.	McDonnell Aircraft Corporation
Solt, Lowell K., Major.	USCONARC, Fort Monroe, Va.
Stein, Benjamin	Bureau of Naval Weapons, Washington 25, D. C.
Stone, Arthur	Bureau of Naval Weapons, Washington 25, D. C.
Stowe, Lewis J.	Curtiss-Wright Corporation
Strok, Michael J., Lt. Col.	Deputy Commander for Aviation USATRECOM
Sutton, J. F., Dr.	Lockheed Aircraft Corporation Georgia Division, Marietta, Ga.
Uberti, Brumo	Piasecki Aircraft Corporation

Vidal, Robert J.	Cornell Aero Lab Inc.
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vonKann, C. F., Brig. Gen.	Director of Army Aviation Deputy Chief of Staff for Military Operations Department of the Army Washington 25, D. C.
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PAPER NO. 1

TACTICAL ASPECTS OF DOWNWASH

by

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TACTICAL ASPECTS OF DOWNWASH

As a member of the US Army Aviation Board and the representative of USCONARC here today, I will discuss the phenomenon of downwash impingement from the standpoint of the users of VTOL aircraft, i.e., the commander who employs these aircraft and the pilot who flies them.

Since the introduction of the helicopter, the history of Army aviation has shown a steady increase in both the number and the proportion of VTOL aircraft. The latest development in this direction is the recommendations of the Rogers Committee, which provides for the supplanting of the L-19, the most widely used aircraft in the Army's inventory, by VTOL aircraft.

Our tactical aviation units must be able to operate in all types of terrain and climates. This requirement encompasses the areas where sand, dust, and snow prevail as well as those areas where grassy meadows are readily available. When we think of Africa and the Middle East, where sand and dust predominate, and the vast area of the globe which experiences heavy snowfall at least part of each year, we realize how important downwash, with its resultant effects, is to the users of downwash producing aircraft.

It has been determined that the erosion of loose dirt and dry sand begins at approximately 2 pounds per square foot of dynamic pressure.[1] For snow the pressure is even less. Since the VTOL aircraft in use by the Army today are of the rotor type with dynamic downwash pressures of approximately 3 to 8 pounds per square foot, snow dust, and dry sand are the surface materials we are presently concerned with. With the advent of vehicles using the unducted propeller and the ducted fan, having dynamic pressures ranging from 10 to 200 pounds per square foot,[2] our concern and problems will be extended to other surfaces such as crushed rock and wet sand. In the battlefield environment, which precludes hard surface, only sod will provide a satisfactory landing zone. For jet VTOL aircraft not even sod, which will withstand dynamic pressures of approximately 1000 pounds per square foot before erosion set in,[3] will be suitable for continuous operation.

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1. Fig. 1 of paper "Considerations of the Effect of VTOL Downwash on Ground Environment," Thomas C. O'Bryan
2. Fig. 3 of paper "General Performance Characteristics of VTOL/STOL Aircraft," Richard E. Kuhn and Marion O. McKinney, Jr.
3. O'Bryan, op. cit.

Perhaps the downwash problem of greatest concern to the pilot is the reduced visibility and loss of ground reference caused by the erosion and recirculation of snow, dust, and dry sand. Allow me to recount an incident which illustrates this point.

It was a bright sunny December 24th several years ago when an H-25 mechanic came rushing into the maintenance office looking for a pilot to test-fly his helicopter. The Christmas spirit was in the air, there was ample time to complete this short flight before the parties would start, and a volunteer was readily forthcoming. In a few minutes the helicopter, in close proximity to a T-33 on the left, a C-47 on the right, and a hangar behind, was warmed up and the pilot started hovering. At that instant chaos developed as the helicopter started moving like a yo-yo in all directions of a 3-dimensional plane. Maintenance personnel started running in all directions, and one man even headed for the crash phone. What the unsuspecting, oblivious pilot had failed to consider was the fact that the apron was covered with 1 to 2 inches of powdery snow from the night before. Although he had been flying instruments regularly in a fixed wing aircraft, it was only by reflex action that he pulled in pitch and got the helicopter out of the snow cloud before it crashed. Gentlemen, added to my other reasons for Christmas celebration that year was the good fortune of not being in the hospital, or someplace worse.

What happened here can also occur where dust and sand exist. To decrease the hazards involved in such operations the aviation commander can assure that pilots are thoroughly oriented regarding the problems and that they are trained in the use of the available flight instruments under such conditions. The technique of moving directly to and from touch-down in one continuous movement without hovering must be used when operating in an area where the recirculation of particles will progressively reduce visibility. However, the above training and technique will not alleviate the visibility problem when the hook-up of external loads is required. Also, in large helicopter operations the reduced visibility from the first aircraft to land will restrict the landing of succeeding aircraft.

Closely associated with the problem of reduced visibility is tactical security. The dust cloud of a single helicopter will signal the enemy's attention to the location of troops, an airfield, or a planned operation. If the air is relatively still the hanging cloud will serve as a marker for the enemy to adjust his artillery upon. Here the commander must weigh the importance to land in a selected landing zone against the disclosure of his position or intentions and the enemy's ability to react. In some areas of the world this may result in the cancellation of missions and operations for VTOL aircraft.

A limiting factor in the employment of VTOL aircraft is the recirculation and instability resulting from the downwash of two or more aircraft operating in close proximity to each other near the ground. Anyone who has flown a helicopter has experienced the problem in landing next to another helicopter which is running up or hovering. Requiring a larger operating area than would otherwise be necessary, the downwash effect limits the number of VTOL aircraft that can be operated similtaneously in a selected landing zone.

To the tactical commander and the pilot of the cargo helicopter the important thing is how much payload can be lifted and transported. With an external load of relatively large x and y dimensions, the payload is reduced by the downwash impingement upon the load. In this situation the downwash is pushing down on the load while at the same time the helicopter is trying to lift it up. Of course, the same problem results from the downwash on the fuselage, but the latter is inherent in the helicopter when the operator gets it, whereas impingement upon external loads is one which he creates in the performance of his mission.

An undesirable product of downwash for the crew, and especially for the ground personnel is the hazard of blowing sand and flying debris. In the desert tests of the H-37 by the Aviation Board, even with the windows and doors closed, the crew had to wear goggles to protect against sand and dust drawn in through the ventilation system. With all openings closed there was fogging of the goggles, intense discomfort, and resultant lowered efficiency for the crew. For the ground personnel it was necessary to wear special clothing during external load hook-ups.

To employthe Army aviation principle of immediate responsiveness it is often desirable to operate VTOL aircraft in close proximity to a unit or command post. However blown-down tents, dusted kitchens, and scattered equipment can quickly lead to "hard feelings," the abrogation of this principle, and the loss of full utilization of the special capability of VTOL aircraft.

Another effect of downwash is the decrease of the lift capability of the helicopter by the clogging of air filters when operating in areas of sand and dust. It is paradoxical that in the area where filters are needed most to protect the engine, the loss of power is unacceptable and the pilot must revert to ram air. Such has been the experience of the Aviation Board in desert testing.

Closely associated with the filter problem is the increased maintenance down-time which develops from the operation of aircraft in sand and dust. Although the user may not be directly responsible for maintenance, the availability of aircraft is a matter of primary important, and directly affects his ability to carry out his mission.

Now, to illustrate a few of the problems I have discussed, I will present a short film showing the experiences of the Aviation Board during various tests.

(FILM, approximately 4 minutes)

In the case of all problems resulting from sand and dust, a possible solution lies in the selection of a sod surface. Yet, in many tactical situations this may seriously impair or preclude the use of VTOL aircraft, thereby negating their advantage. Soil treatment or the use of a material such as vinyl may be used in limited situations. However, these measures are totally infeasible for operations beyond the front lines or for large scale operations.

Gentlemen, as a layman I have presented some of the layman's problems and possible solutions pertaining to downwash impingement. Please keep in mind that I have been talking about aircraft with downwash pressures of 3 to 8 pounds per square foot. It takes only a little imagination to project the magnitude of these and other problems involved in the tactical use of aircraft with downwash pressures in the hundreds of pounds per square foot.

To you, the engineers, designers, and builders of VTOL aircraft, the Army, as the largest user of these aircraft, requests that you give special attention to their suitability for tactical employment.

We must have aircraft which can operate anywhere on the battlefield.

PAPER NO. 2

NAVY PRESENTATION

by

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(Copy not available at time of publication)

PAPER NO. 3

ARMY RESEARCH IN DOWNWASH PROBLEMS

by

Mr. Robert Graham
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USATRECOM, Fort Eustis, Virginia

ARMY RESEARCH IN DOWNWASH PROBLEMS

The problems associated with the downwash from devices which produce lift at zero forward speed have become increasingly serious over the years since the advent of the helicopter. Some of the problems experienced with helicopters have been described by the previous speakers. The advent of VTOL aircraft utilizing relatively small rotors, propellers, or jet engines, all of which have much higher downwash velocities than that of the helicopter, has accentuated the seriousness of the old problems and has introduced some new ones.

Our purpose today is to review the current research effort on these problems with the dual purpose of disseminating information to those not already aware of recent findings and to review and consider possible future areas of research. With regard to the latter objective, it is hoped that during the discussion period scheduled for this afternoon, suggestions will be offered that may be of aid in planning our future programs.

As of the present time, Army aviation interest has not extended into the field of direct-lift jet engines. For this reason, downwash research supported by the Army has been limited to that in connection with rotors or propellers. However, many of the problems are similar regardless of the source of the downwash. Thus, this symposium was planned to review all of the downwash research to date.

About two years ago, the Army initiated an extensive program for investigating these problems. The main portion of the work performed to date has been concerned with a better definition or understanding of the downwash flow field and its associated erosion effects. This work is being performed by Hiller Aircraft Corporation under a USATRECOM contract and by Kellett Aircraft Corporation under a BuWeps contract. Both contracts are being funded jointly by Army and Navy. The Hiller work consists of velocity surveys in the flow fields from open and ducted rotors, and measurements of erosion and particle movement caused by these rotors operating over various ground conditions. Details of the Hiller work will be given later by Mr. Morse of that company. The Kellett work will be somewhat similar to the Hiller work but at a larger scale. Details of the Kellett work will be given later by Mr. Goland of that company and Mr. Stein of BuWeps.

Some work has been started on a search for solutions to the problems. One portion of this search has been performed by Cornell Aeronautical Laboratory and will be described in detail by Mr. Vidal in a later paper. Another portion is being performed by the Corps of Engineers at the Waterways Experiment Station and will be described

in a paper by Mr. McInnis. Still another portion is being performed under an Army-European Research Office contract by the National Research Laboratory of Amsterdam, Netherlands. That laboratory is not represented at this symposium; hence, I will briefly describe their work.

Their main effort is being concentrated on determining methods of expanding air jets so as to reduce the velocity of the air near the ground. Two methods of spreading the jet will be investigated experimentally on the device shown on the first slide. Dimensions shown are in millimeters. A compressed air source feeds air into the plenum chamber. The air then flows through a 9 to 1 contraction to the nozzle. Thus, an air jet is produced which simulates the flow from a ducted propeller about one foot in diameter operating at disk loadings up to about 100 pounds per square foot. The device is mounted on strain gages for thrust measurement and a plate simulates the ground.

Two methods to be investigated for spreading the jet are shown on the next slide. One method consists of coaxial diffusers utilizing the jet flap principle to achieve the diffusion. The other method consists of introducing a strong rotation to the slipstream, and vanes utilizing the jet flap principle produce the swirl. The results of these tests will determine if further tests with normal flaps or diffusers are warranted. The effects of these devices on the power requirements and thrust will be determined. This program is a low budget item. The experiments will not be completed until June 1961 and reports on the results will not be available until sometime thereafter.

Hiller has prepared three reports on their work thus far. The first one, covering the velocity surveys, has been published and given a limited distribution. Additional copies have now been printed and were distributed to you at the registration desk. The second report, covering the soil erosion tests, is in the process of publication. The third report covers soil erosion tests with simulated dual jets and ground effect machines and this report, too, is in the process of publication. A fourth report summarizing all of their research effort to date is being prepared. Copies of these reports will be distributed as they become available.

Cornell has just published a report on their initial effort. That report will be distributed here today.

It is intended that future work will place more emphasis on searching for solutions to the problems involved. We will, of course, continue to obtain better definition of those problems in areas where a need is found to exist.

Some work in the field of soil stabilization or ground cover will also be performed. The Waterways Experiment Station has a background of experience in this field and they will work with us in this area. This type of solution, however, is not the ultimate that the Army would like to find. For maximum mobility, the preferred solution would be one that would permit operation from areas that have no advance preparation. For this reason, possible solutions that do not involve changes to the ground surface will receive primary attention. It is hoped that this symposium will provide an excellent summary of past work and current thinking to serve as a guide for future programs.

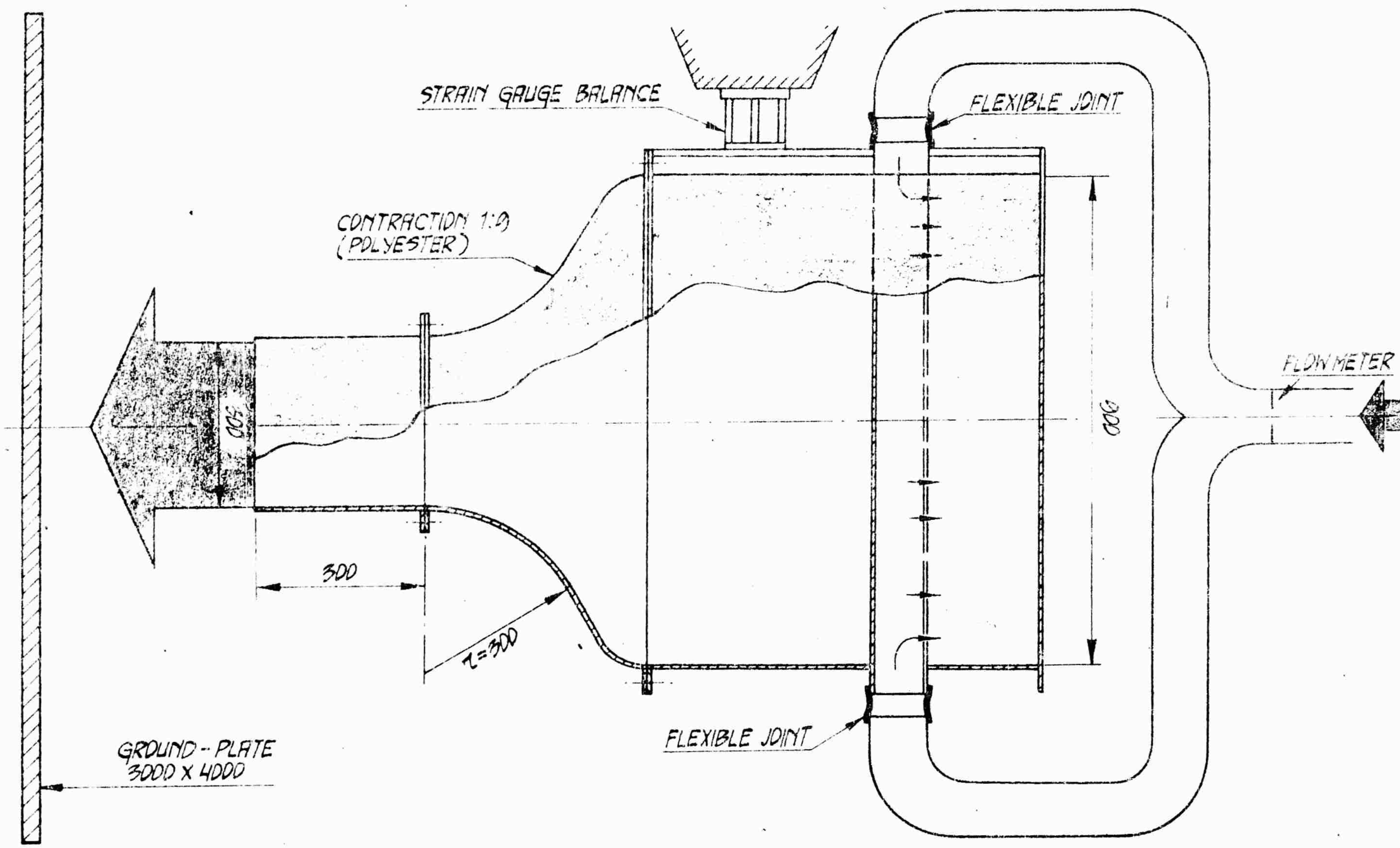

Fig.1 Experimental set-up for VTOL ground erosion test.

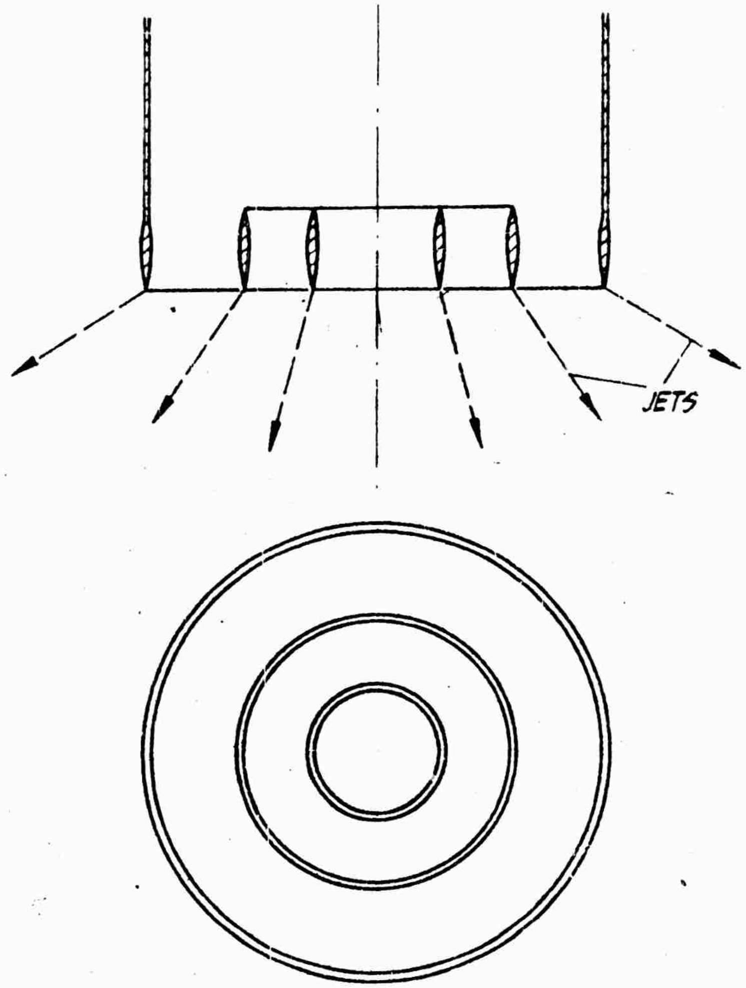

Fig.2 **Diffusor with jet-flaps in jet exit.**

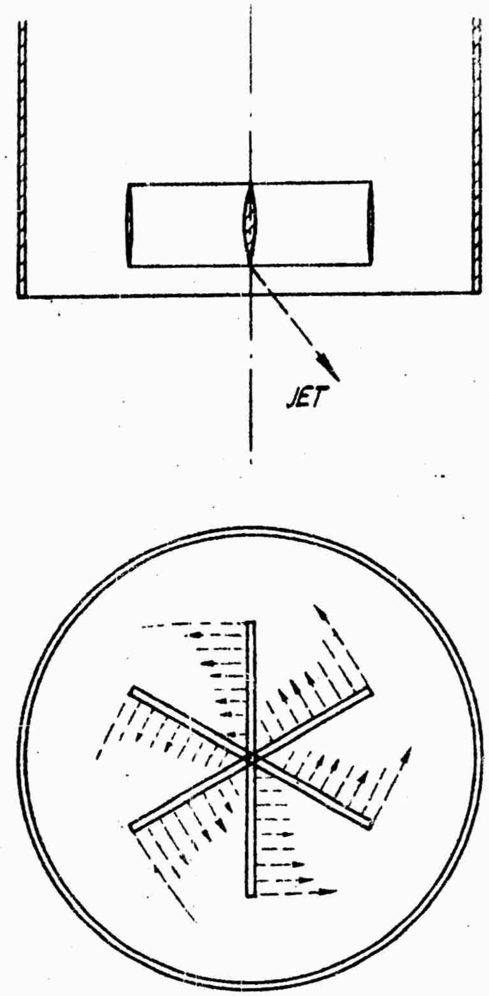

Fig.3 **Cross with jet-flaps in jet exit.**

PAPER NO. 4

DOWNWASH AND RECIRCULATION STUDIES

by

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DOWNWASH AND RECIRCULATION STUDIES

In January 1960, the Propulsion Laboratory of WADD initiated a series of empirical tests to assess the erosion problems associated with VTOL aircraft powered by turbo-jet engines. Using a YJ85-GE-3 engine as a power source, several surfaces were tested. These surfaces included: a hard packed sand, gravel, dirt mixture; good sod (heavy root structure); concrete; and sod covered with pierced steel planks. No attempt was made to define numerically the damage resulting from these runs, nor was any attempt made to measure downwash velocities or temperatures. The follow-on program has provided us with velocity and temperature data, so that at this time, we can accurately define the impingement plane conditions and qualitatively define the damage under these conditions.

The following film clip dramatically shows the results of a run over sod.

These opening scenes show the engine as it is mounted on the fork lift. As will become obvious, the engine is tiltable; however, these movies do not show the versatility of the rig completely, as we can actually simulate a take-off using remote controls on the lift mechanism of the Hyster.

We are now starting the tilting sequence of the engine. In most cases, the engine is started in a horizontal position and brought up to idle. It is then tilted to the vertical position and accelerated to military. Acceleration time for this particular engine is about 13 seconds and the duration of the entire run you are witnessing is approximately 20 seconds from the throttle advance time to the time the throttle was retarded and the reverse tilt cycle initiated.

These next scenes show quite dramatically the environment in which the engine must operate if running over sod is necessary. It will be noted that not only are we eroding small particles of dirt, etc., but large chunks of dirt and grass are being eroded and carried throughout the area. This movie documents the fact that any ground equipment in the immediate area might be damaged, and also that pilot visibility would probably be restricted.

At this point, we started decelerating the engines and tilting it back to the horizontal position. A longer run had been planned, but due to the obvious dirt ingestion and the possibility of engine failure, it was cut short. Unfortunately, we have no instrumentation for measuring thrust on this set up; otherwise, it would have been beneficial to know how much engine performance was degraded by this exposure to damaging ingestion.

This next scene shows the bellmouth and inlet screen. As can be seen, some grass and straw are stuck to the screen, indicating that quite a bit of recirculation was present during the run, accompanied by foreign object ingestion. The bellmouth, center section and cylindrical inlet section had the appearance of being sand blasted. Upon removal of the aforementioned pieces, no damage to the compressor could be seen. After this run, a series of tests over semi-prepared and prepared surfaces were run with the same engine and no operating difficulties were encountered that could be attributed to foreign object ingestion.

The last two scenes show the results of this 20 second run. The two engineers near the hole give some idea of the size; however, rough measurements indicate the following: 6 to 7 feet long, 4 to 5 feet wide, and 6 to 10 inches deep.

As can be seen, the soil was damp and the root structure of the turf was quite heavy. As has been previously mentioned, however, no attempt was made to determine water content or type of soil.

For those of you who are not familiar with the performance of the YJ85-3, I have some figures which indicate the conditions under which this test was made. The thrust of the engine is 2250#. This gives a radial surface dynamic pressure of approximately 1030 P.S.F. and a temperature of 875° F with the exit nozzle 5 feet from the surface.

This short resume' concludes what I have to say about the past program other than the fact that a WADD Tech Note 60-183 is available covering the program more completely.

As a point of interest, I would like to describe a quick test that we made for our Materials Laboratory between the current program and the previously described program. The test involved running over one of the industry developed plastics. We made a full scale simulated take-off run over the surface and our data correlated quite nicely with model tests with one exception. The model tests indicate that more than one take-off run could be made with only minor repairs being necessary, while our run showed that extensive repairs or a complete new surface would be necessary after each take-off.

Our current program, entitled "Downwash and Recirculation Studies", was initiated in August of this year. The purpose of this program is to define the downwash and recirculation temperatures and velocities of a full scale jet engine. We are utilizing the same test rig as was previously described; however, extensive temperature and pressure instrumentation has been added.

The areas we are looking at, and hope to define by testing, are shown on this chart. In Zone I, there is very little controversy. Over many years, researchers have been making tests and analytical descriptions of this area and it is very well defined.

Zone II is not so well understood. In our case, not only is it not understood, but we find it is a difficult area in which to obtain accurate test data. We find too that this area is one in which information is needed, particularly with regard to temperature.

In Zone III, the free expansion is fairly well understood, and some analytical expressions have been derived. However, the most accurate prediction methods are still based, to some extent, on empirical relationships.

In Zone IV, we find that very little is known about the recirculation and very little test data is available. This region is particularly difficult to analyze since it is dependent upon aircraft configuration. It is felt, however, that an accurate description of this area might well be the deciding factor in determining take-off performance. For example, using a typical turbo-jet VTOL aircraft with an over-all thrust to weight ratio of 1.05, at ambient temperature, a 20°F rise in temperature due to recirculation would make a vertical take-off marginal if not impossible.

This schematic shows our instrumentation set up. The tall stand of directional pitot tubes is used in the free expansion zone and to some extent in the recirculation zone. It is mobile and to date, surveys have been run starting at 2 feet from the center-line out to 10 feet. Due to a hold-up in data reduction, only selected points have been calculated, and therefore, very little can be said about the results in this region.

The small stand of pressure and temperature pickups is used in the free expansion zone and in part of the turning zone to measure horizontal radial velocity. On the previous chart, I indicated the effective region of the stand as Zone V. All the data from this stand has been reduced, and I will have more to say about it in a few moments.

The ground rake is not movable, however, it provides data in the impingement area. Theoretical predictions are fairly accurate in this area and correlate quite well with the data we have. It is from this rake and the small mobile rake that we have made predictions as to the impingement plane conditions of our previous erosion testing.

The last piece of instrumentation is the series of thermocouples around the bellmouth. We hope to be able to measure any exhaust gas recirculation with these, but to date no data has been plotted. Therefore, nothing can be said other than the fact that it is obvious from watching selected thermocouple readings that recirculation is present and that it is degrading our engine performance.

As in the previous test, we have no way of measuring thrust. However, we have done the next best thing. The engine was mounted on a thrust stand and a set of calibration points taken. These points were then plotted and extrapolated for both temperature and pressure such that on any given day, the actual performance of the engine can be calculated very closely. At the completion of testing, the engine is again scheduled for a calibration run. Since this engine is very stable with regards to performance degradation as a function of time, it is anticipated that very little difference will be found in the two calibrations and that a very accurate picture of engine performance can therefore be obtained.

Again referring to the flow chart, it was previously mentioned that Zone V merits particular interest. All our data, to date, has been reduced and plotted on a chart which was obtained from General Electric and is based on the theory that: "(1) for a jet directed normal to the ground, the maximum radial velocity at any distance greater than 1.16 diameters from the source is independent of disc loading".

This graph shows radial velocity plotted against radial distance on a log, log scale. The line shown was empirically derived and applies only to Zone V. Data used to obtain this line encompasses quite a range of disc loading including: 1 and 4 inch air nozzles, turbo-props, helicopters, and lift fans. Note, this data covers quite a velocity range, but for cold gas only. The equation of the line is: $V = \frac{26.8\sqrt{F}}{X}$ where V is the actual radial velocity in ft/sec, F is scaled thrust in pounds, X is the scaled radial distance in feet, and 2618 is an empirically defined constant.

(1) General Electric, Flight Propulsion Laboratory Department
Propulsion - Vol. I, No. 21
Downwash from Lifting Devices by P. J. Hess

The scaling method used to plot this diversified data is as follows:

The actual nozzle exit plane dynamic pressure is held constant and a nozzle diameter is calculated, using this constant, which will give a jet of 23,000 pounds thrust. The ratio of the calculated nozzle diameter to the actual nozzle diameter is then multiplied by the actual radial distance The scaled radial distance is then plotted against measured radial velocity.

Now, using this scaling method and data obtained from the YJ-85 engine, the circled points were obtained. The maximum error of any one of the eight points is 16%. Considering that this highest error point was taken during a high wind condition and that the thrust of the engine was calculated rather than measured, this error is not excessive.

We hope to be able to take some of these higher error points over again in a no-wind condition and with the addition of the more accurate and extensive data we should be able to prove or disprove the theory as far as hot gas is concerned.

It should be pointed out that from the randomly calculated points, we seem to have some correlation with both theoretical and model data. However, we are not convinced that any model hot gas data or any full scale cold gas data is directly applicable to the problems involved with full scale hot gas.

In conclusion, I should like to briefly describe the status of the program and what further testing we hope to do.

At present, we are running the velocity and temperature surveys on an unscheduled basis as manpower is available. We hope to have all our data in about 8 more hours of running.

Then, since we feel that our data is only typical of a wing tip mounted rotating engine, we hope to include some generalized planform testing. As stated, this would be very general testing, but it should give us a better idea of exhaust gas recirculation.

This concludes what I have to say, except that any comments or suggestions would be appreciated, and also, if any of you in the audience are visiting at WADD, I would be more than happy to talk with you and show you our test set-up

PAPER NO. 5

PROPOSED INVESTIGATION OF VTOL DOWNWASH BLAST EFFECTS

by

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PROPOSED INVESTIGATION OF VTOL DOWNWASH BLAST EFFECTS

Extensive new facilities for studying the effects of blast from jet engines, rocket motors, and guided missiles are now being constructed at the U. S. Army Engineer Waterways Experiment Station in Vicksburg, Miss. These facilities are required for use in the investigational programs of assigned Corps of Engineers' research and development projects. When completed, the installation will also be capable of producing velocities and temperatures associated with helicopters and VTOL and STOL aircraft.

Major components will be housed in a building about 50 ft square and will consist of rocket engines with various nozzle configurations, compressed air engines for tests with clear plastic models, a jet aircraft engine for testing designs and materials normally found around an airfield, bladed propellers and ducted fans to simulate aircraft blast on various types of soils and on dust alleviators, and a movable test rig or bed to allow simulation of effects caused by high-velocity hot gases as a missile rises from its launch pad. Also, the installation will have the necessary instrumentation to record all phenomena such as gas flow, pressures, velocities, and temperatures. Photography will consist of the conventional methods and also the Schlieren system using high-speed motion picture cameras. I have two slides I would like to show now of these facilities which are not yet completed.

In view of the recent increased emphasis on the effects of downwash impingement from helicopters and VTOL aircraft and the numerous requests for basic data concerning the effects of hot and cold gases impinging on various materials or surfaces, we have proposed to the U. S. Army Transportation Research Command that these blast-effects facilities be utilized to conduct an investigation with small-scale models and small engines to simulate downwash blast effects on soils, vegetation, and various materials. The preliminary phase of this proposed investigation will be to determine the ability of scale models to indicate prototype results for rotary-wing aircraft, ducted-fan and turbo-fan aircraft, and pure-jet and augmented-jet VTOL aircraft.

Present indications are that the downwash blasts of present and future aircraft may vary through a wide range of velocities, mass flows, and temperatures; that they will originate at various heights above the ground; and that they will be directed toward the ground at various angles. Also, blast probably will be generated by multiple as well as single units and these must be considered.

The surface on which an aircraft operates may be damaged by heat of the blast, or the particles making up the surface may be displaced or eroded by the blast. Either type of damage could occur quickly or over an extended period of time. In the case of particle displacement,

the sizes of the displaced particles will influence the nature of the damage which might be incurred. Finer particles tend to form dust clouds which interfere with pilot visibility, cause damage to the aircraft, and are otherwise objectionable. Larger particles or small free objects which become airborne may damage nearby aircraft, equipment, or structures or may injure personnel.

Generally, the characteristics of the downwash blast of an aircraft are known or can be determined with reasonable accuracy. It is generally felt that it should not be necessary to conduct full-scale tests with each new aircraft to determine the effect of its downwash blast on various surfaces. Hence, the approach proposed in this study is to obtain basic data on the effect of the flow of hot and cold gases on and against various surfaces under a range of test conditions which will encompass the general downwash characteristics of these aircraft.

As mentioned a moment ago, a specific early objective of this test program is to establish that relatively small-scale models can be utilized to duplicate or closely approximate the effects of the full-scale aircraft. It is proposed to accomplish this by comparing the effects of full-scale aircraft with properly scaled small models. Obviously, for comparisons to be made, data from both full- and small-scale equipment must be available. In some cases, information obtained from full-scale tests on effects of the downwash under a variety of conditions may be known. In other cases such information will have to be developed under this test program.

If required, full-scale tests with rotary-wing aircraft can be conducted either at Fort Bragg, N. C., or Fort Rucker, Ala., in conjunction with other studies now being made at those locations by the Waterways Experiment Station. Various types of rotary-wing aircraft are available at each location, and one test area can be set up and a number of tests with these aircraft can be conducted in a very short period of time. Instruments would be used in these full-scale tests to determine downwash velocities caused by the rotors, velocity patterns along and above the ground surface, and the areal extent of disturbance produced by the downwash blast.

With such full-scale data, scale factors will be determined for small models to be constructed and utilized in studying the general effects of downwash blast of this type aircraft. These models will consist mainly of small rotors driven by electric motors.

Once the scale models indicate good simulation of the full-scale aircraft blast, determination will be made of the velocities at which soil particles are lifted into the air and become detrimental to pilot visibility and aircraft operation. This particular phase of the study could lead to the development of either a visibility device that could

be used by an aircraft pilot to determine safe operating conditions where dust is involved or just a "rule of thumb" that would indicate safe aircraft operating conditions if dust is not formed when the aircraft is at or below a certain critical height from the ground. These small-scale model studies will be the basis for tests to be conducted later using the higher velocity thrust-type aircraft; therefore, a number of variables will be considered in these initial tests before advancing to other groups of VTOL aircraft.

The ducted-fan and turbo-fan VTOL aircraft are relatively new, and most of the data needed to study them on a scaled-down basis will have to be obtained from the manufacturers or by working with the aircraft. The basic difference between this type of aircraft and the rotary-wing type is that the mass flow of downwash is concentrated in a small area, thus producing higher velocities. To simulate this modelwise, manifolds of various diameters and configurations will be used and the air flow will be produced by fans and compressed air. These studies will be centered around the area of high-velocity downwash impingement, with the data obtained from the rotary-wing studies being utilized where possible in those areas where high velocities decay to small values. Specific areas to be observed modelwise would be the number of landings and take-offs possible over specific types of soil surfaces and vegetation and also the effect of downwash recirculation on the operation of the aircraft engine and on pilot visibility during landing and take-off. The interactions of the downwash blasts from miltiple-unit configurations on soil surfaces and materials will also be studied in this phase.

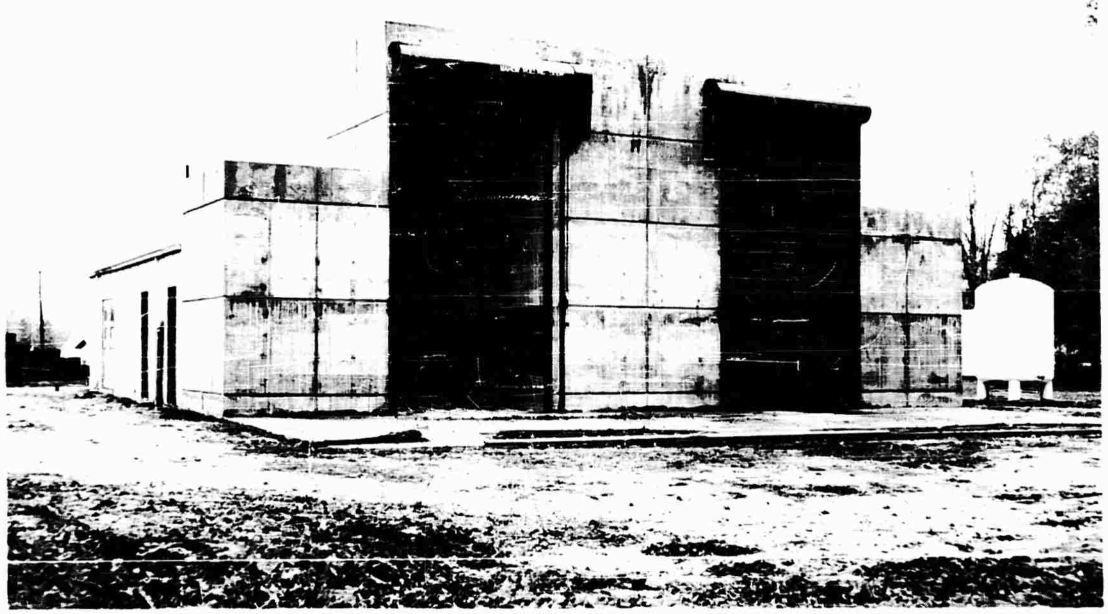
The pure-jet and augmented-jet VTOL aircraft will introduce not only still higher downwash velocities but also higher temperatures. Data on downwash blast characteristics of these aircraft will be obtained from the manufacturers where possible and from agencies conducting experimental or acceptance tests. Small-scale tests of this group can be conducted using a relatively low-thrust jet engine which will produce the velocitics and temperatures desired. Multiple-unit propulsion systems of the pure-jet aircraft will be scaled down by manifolding off the jet engine exhaust. For the augmented-jet VTOL aircraft (which draws in outside air to augment the high-velocity exhaust gases for lifting), the exhaust blast of the jet engine can be directed into a manifold so fabricated as to allow control of inlet air. The shape of the manifold of course will be dictated by the aircraft being studied in the tests.

Since higher velocities are present with these aircraft, the sizes of free-flying soil particles and loose objects will be greater; thus, the downwash recirculation problem may be more serious and aircraft operations more dangerous. The studies with the pure-jet and augmented-jet VTOL aircraft group should allow selection of limits in which these aircraft could operate safely. Also, the number

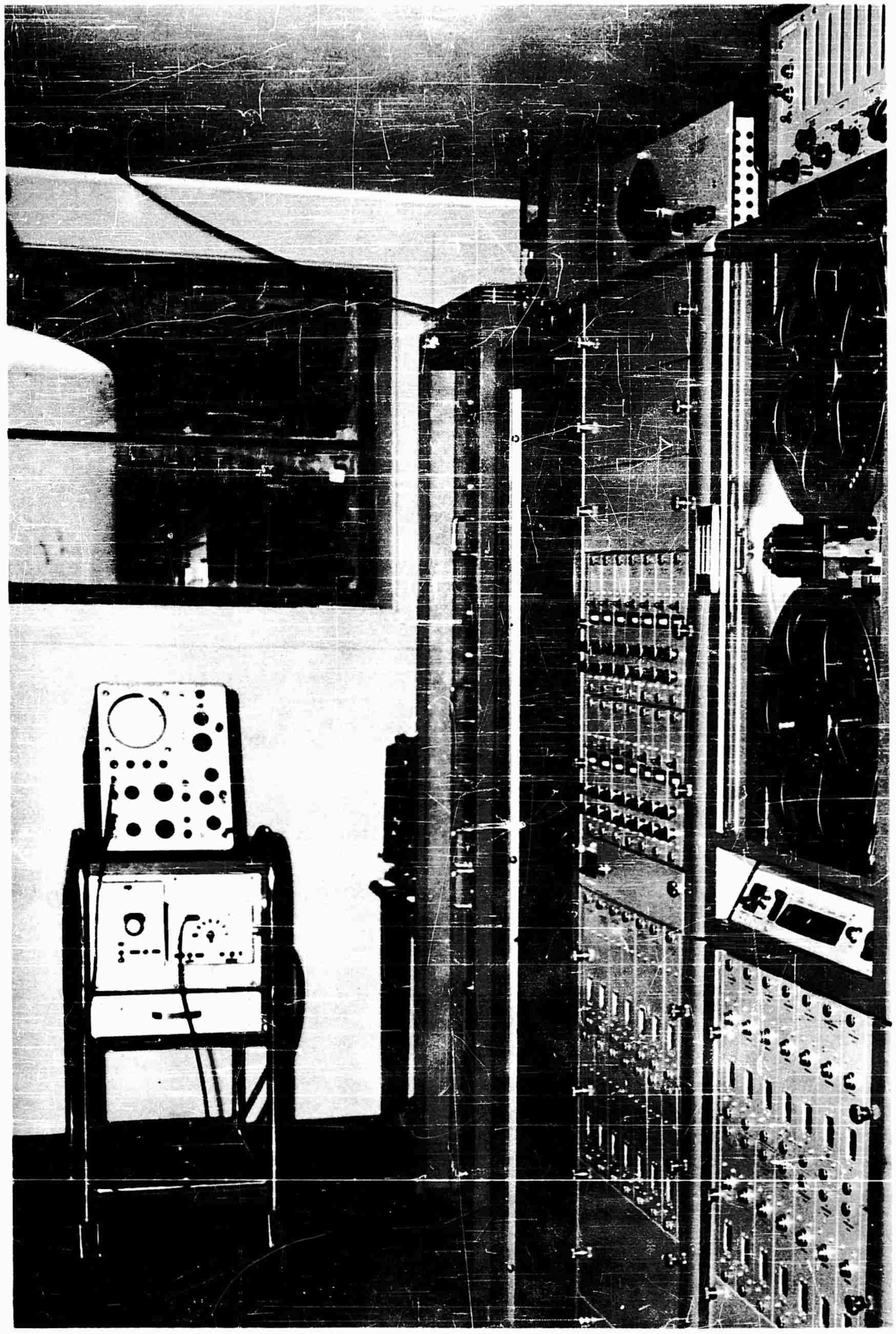
of landing and take-off cycles possible on various soil surfaces and materials will be studied.

In conclusion, these scale model downwash blast studies should yield data which, when plotted graphically, indicate which type of aircraft can operate safely over specified soil surfaces, vegetation, and materials. These data would be applicable to aircraft available during the study. However, should a new aircraft be developed in the future with characteristics similar to an aircraft already studied, the downwash effect of the new aircraft could be predicted from the data obtained in this proposed study. Should the newly developed aircraft have radically different characteristics from those aircraft previously studied, additional small-scale model tests would be required.

These are ideas for one approach to the downwash problem. For the Corps of Engineers, the obvious corollary to this proposed investigation will be a study to determine the most feasible and expedient means of controlling dust and erosion generated by the downwash blasts of these aircraft.



Slide 1. Experimental Facilities for Investigating Downwash Blast Effects.



Slide 2. Instrumentation Room of Experimental Facilities.

PAPER NO. 6

NAVY RESEARCH IN DOWNWASH PROBLEMS

by

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NAVY RESEARCH IN DOWNWASH PROBLEMS

I. INTRODUCTION

The advent of new generation VTOL aircraft has brought with it problems associated with high downwash velocities. Early tests on small scale models indicated serious ground erosion problems may be expected over certain types of terrain and indicated a need for additional full-scale research on the downwash problem. The program I will discuss at this time is an attempt to provide systematic full-scale information on downwash problems over various types of terrain and downwash effects on personnel and equipment. This program is being conducted by the Kellett Aircraft Corporation under the joint sponsorship of the Bureau of Naval Weapons and the Army TRECOM.

II. OBJECTIVE

The objective of the Kellett full-scale test rig program is to conduct full-scale investigations of the effect of rotor downwash on terrain and the surrounding area at disc loadings up to 60 pounds per square foot.

III. TEST EQUIPMENT

A 4360 20-WC engine driving a four-bladed 15-foot diameter propeller will be mounted on the boom extension of a 20-ton Bay City truck crane. The truck crane concept was chosen to provide ease of portability. This engine propeller combination will be capable of producing approximately 11,000 pounds of thrust at disc loadings from 0 to 60 pounds per square foot at heights of 11 to 40 feet above the ground, or .7 to 2.7 propeller diameter heights above the ground. The propeller will also have the capability of being tilted to an angle of 30° from the vertical.

IV. TEST INSTRUMENTATION

A. Provisions are made for recording the propeller position in regard to height above the ground and angle of inclination of the thrust vector.

B. Four load cells are provided to measure the propeller thrust.

C. A static pressure rake will be used to determine the ground pressure distribution.

D. A hot wire anemometer is provided to sense and indicate airflow velocities near the ground level.

E. Three motion picture cameras are provided to afford integrated motion picture coverage of the experimental tests from three different vantage points.

V. DATA TO BE OBTAINED

For a given test condition of the propeller, data will be obtained relative to:

A. The airflow

B. Effects on the terrain

C. Effects on the test rig

D. Effects of impingement on material and/or personnel

A TEST CONDITION WILL CONSIST OF:

A. Propeller Height (0.7, 1.7, or 2.7 times propeller diameter)

B. Propeller Thrust Angle (0 to 30 degrees)

C. Disc Loading (10, 40 or 60 psf)

D. Terrain Type and Configuration

THE FOLLOWING DATA WILL BE OBTAINED FOR EACH TEST CONDITION:

A. Ground static pressure distribution at eight locations along a typical radius at 7.5 foot spaces starting from propeller centerline.

B. Airflow velocities near the ground for several heights up to 4 feet.

C. Photographic coverage of terrain disturbance, erosion of impingement material and effect on objects placed in downwash field. Objects such as large rocks, oil cans, crates, equipment, etc., will be used in the investigation.

VI. DESCRIPTION OF TERRAIN

Tests will be conducted over terrain in its natural state wherever possible. This requires the test program to be as flexible as possible to take advantage of various weather phenomena. Each group of tests will be conducted over:

A. Concrete or Macadam, clean

B. Concrete or Macadam, debris strewn

C. Sod

D. Clay

E. Earth

F. Water

G. Snow

H. Sand

I. Gravel and stone mixture

The terrains listed above will be tested starting from hard surface and progressing toward more granular materials until operational limits are encountered.

VII. CONCLUDING REMARKS

The program outlined above is primarily exploratory in nature and somewhat limited in scope. It is aimed primarily at uncovering problems rather than solving them, although simple solutions will be examined during the program if feasible. Additional work to be done will depend in part on the results of this investigation and on others being conducted in industry and by the other services. Among areas where additional work may be necessary and where perhaps work is going on in private industry, are the following:

A. Effects of vehicle motion relative to the ground on the downwash problem.

B. Effects of dust and debris ingestion on engine operation and determination of simple methods of relieving the engine ingestion problem.

C. Effects of airframe configuration and air intake location on the ingestion problem.

D. Effects of multiple rotor arrangements.

E. Effects of various airplane - propulsive device configurations, i.e., tilt wing, tilt duct, tilt propeller, fan-in-wing, on downwash problems.

F. Effects of downwash recirculation on aircraft flying qualities.

G. Effects of high downwash velocity on general operational suitability.

I would like to show a brief movie of the test rig which shows more graphically the test set-up described previously.

PAPER NO. 7

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION RESEARCH ON DOWNWASH IMPINGEMENT

by

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NASA RESEARCH ON DOWNWASH IMPINGEMENT

INTRODUCTION

NASA research in the field of downwash impingement has not been very extensive to date because most of the manpower available for work in the V/STOL field has been used in research on a number of pressing problems in other areas such as aerodynamics, handling qualities, and loads. We have done some work on downwash impingement problems, however, and have plans for continued work along this line. Since most of the downwash research by the NASA was covered at the recent V/STOL conference held at Langley, only a brief summary of this work will be given in this paper, along with some indication of our plans for the future.

The areas covered in downwash research by the NASA are shown in figure 1. There are three general areas involved - surface erosion, slipstream flow along the ground, and slipstream recirculation. The slipstream recirculation research is concerned with three different aspects of the problem - recirculation of debris and effects on the performance and handling qualities of the aircraft. It is realized that items B and C are outside the scope of this symposium, but it was felt appropriate to indicate that these are two important aspects of the over-all downwash problem with which we are concerned. And the research on these items should also yield information of value in connection with item A. There will be no further comment on these two items except to point out that we are particularly concerned with the effects of slipstream recirculation on handling qualities of VTOL aircraft because flight research to date has indicated this is a definite problem area requiring further research.

SURFACE EROSION

Our only completed work on surface erosion is the small-scale work done by Kuhn and reported in reference 1. This study showed that the onset of erosion depends on the dynamic pressure of the outward flow of air near the surface. Data were obtained which indicated that erosion of sand and loose dirt started at surface dynamic pressures of 1 to 3 pounds per square foot, but the onset of erosion could be delayed to dynamic pressures of 30 to 50 pounds per square foot by thoroughly soaking the sand or dirt. The tests also showed that good dry sod could withstand dynamic pressures up to 2,000 pounds per square foot, but this result was not considered to have general application because it was obtained with a small-diameter cold jet.

Although it appeared desirable to follow up this small-scale surface erosion work with research at higher scale including the use of hot jets, very little has actually been done along this line for two reasons: first, a shortage of NASA personnel available for such research; and second, an indication that some of the desired information would be obtained by other organizations under contract to the services. We are now in the process of doing one bit of research on surface erosion with the Curtiss-Wright X-100 airplane shown in figure 2.

The X-100 is a small VTOL research airplane of the tilt-propeller type with two 10-foot-diameter propellers mounted at the tips of small stub wings. Curtiss-Wright built the airplane as a company project and it has been flown by their test pilots and also by one of our NASA test pilots. Following completion of the company flight test program, the machine was loaned to Langley for use in downwash studies. The T-53 engine installed in the airplane for these tests is on loan from the Army. The surface erosion work to be done with the X-100 will consist of tie-down tests of the airplane over various types of terrain at slipstream dynamic pressures up to about 25 pounds per square foot. One point of interest in these tests is that the effects of two slipstreams side-by-side will be determined. Most of the previous surface erosion work has been done with a single slipstream.

SLIPSTREAM FLOW ALONG THE GROUND

The subject of slipstream flow along the ground has recently received quite a bit of attention in connection with the problem of sliding or blowing over objects around the take-off and landing area. One interesting point that has been brought out in research in this area by the NASA and others is the fact that the problem of blowing over objects may actually be less severe for higher-disk-loading VTOL aircraft than for helicopters. This point is illustrated in figure [illegible] which was used in the recent V/STOL conference at Langley. This figure shows the decay of slipstream dynamic pressure with distance along the ground from the center line for two rotors having disk loadings of 10 and 40 pounds per square foot and lifting a gross weight of 40,000 pounds. At distances up to about 1 rotor diameter from the center line, the high disk loading machine produces much higher dynamic pressures, but beyond this point the dynamic pressure is about the same for the two cases. Since the slipstream flow along the ground is much thicker for the low disk loading rotor, it would appear that at these greater distances where the dynamic pressures are equal the tendency to overturn objects on the ground would be greater with the low disk loading. A point of basic importance to be brought out in connection with this figure is that the slipstream dynamic pressure along the ground some distance out from the center line is not a function of disk loading, but merely a function of the gross weight or thrust of the aircraft.

Figure 3 covered the case of the single slipstream. Figure 4 shows how the flow along the ground is altered when there are two and four slipstreams involved. Dynamic pressure contours along the ground are shown for tilt-wing models having two and four propellers. The solid lines are the measured contours for a q equal to 0.4 the slipstream q, while the dashed lines represent the estimated contour for a single propeller assuming there are no other propellers present. The data show that there is a definite buildup in q along the longitudinal center line of the aircraft. Apparently the slipstream reinforce each other as they spread outward along the ground and meet at the plane of symmetry. Note that the $0.4q_S$ contour line extends about as far forward as it does to the side. Actually, for greater distances out from the center of the aircraft, the dynamic pressure becomes greater in front of than beside the aircraft. This point is illustrated in figure 5 which shows data obtained on the Vertol VZ-2 and Doak VZ-4 airplanes.

Figure 5 shows the variation in q along the ground with distance from the center of the aircraft measured side-to-side along the lateral axis and fore-and-aft along the longitudinal axis. The data show that near the center of the aircraft the q is greater along the lateral axis but at greater distances from the aircraft the q is greater along the longitudinal axis, apparently because of the reinforcing effect of the slipstreams in this direction.

SLIPSTREAM RECIRCULATION

The NASA has undertaken a general study of recirculation phenomena because of the importance in connection with performance, handling qualities, and operating problems of VTOL aircraft. This work involves the testing of small-scale models of various VTOL configurations, and also, wherever possible, full-scale VTOL aircraft, such as the Curtiss-Wright X-100. Some information on recirculation of debris was obtained recently at Langley with the Vertol VZ-2 in flight tests that were not intended to involve ground impingement phenomena. (See ref. 2) While performing a taxiing turn with the wing tilted up 76° after landing on a [illegible] overrun covered with loose and embedded gravel, the airplane was damaged when gravel was thrown up by the recirculating slipstream. All of the propeller and tail fan blades sustained some damage, as did the first-stage stator and rotor blading of the engine. The aircraft structure itself was not damaged but the upwash deposited a great deal of dirt and small stones in the cockpit and open fuselage. In our research in this area of slipstream recirculation, we hope to provide information regarding the mechanism by which dust and debris are recirculated with different arrangements of slipstreams and jet exhausts; and, of course, we also hope to come up with suggestions for minimizing this problem wherever possible.

CONCLUDING REMARKS

In conclusion, I would like to emphasize that the NASA is very much interested in the over-all downwash impingement problem because of its importance in determining the degree of success which can be realized by operational VTOL aircraft of various types. We are expecting to have an increasing research effort in this field in the future.

REFERENCES

1. Kuhn, Richard E.: An Investigation to Determine Conditions Under Which Downwash From VTOL Aircraft Will Start Surface Erosion From Various Types of Terrain. NASA TN D-56, September 1959.

2. Pegg, Robert J.: Damage Incurred on a Tilt-Wing Multi-Propeller VTOL/STOL Aircraft Operating Over a Level Gravel-Covered Surface. NASA TN D-535, December 1960.

NASA DOWNWASH RESEARCH

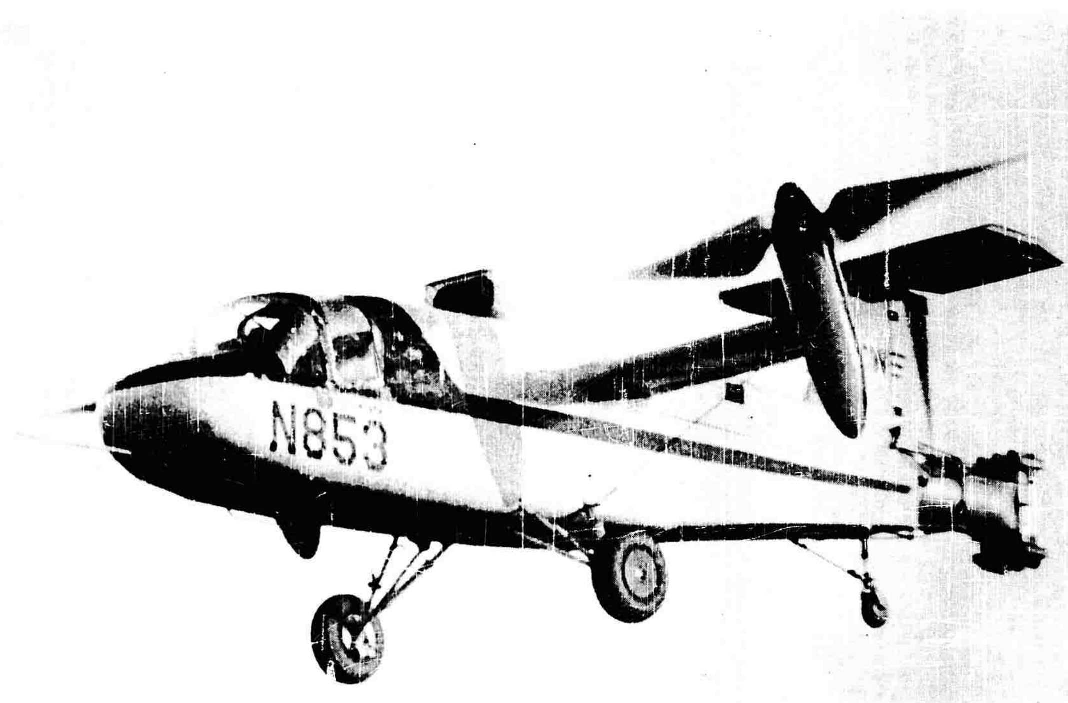
1. SURFACE EROSION

2. SLIPSTREAM FLOW ALONG THE GROUND

3. SLIPSTREAM RECIRCULATION
   - A. RECIRCULATION OF DEBRIS
   - B. EFFECTS ON PERFORMANCE
   - C. EFFECTS ON HANDLING QUALITIES

NASA

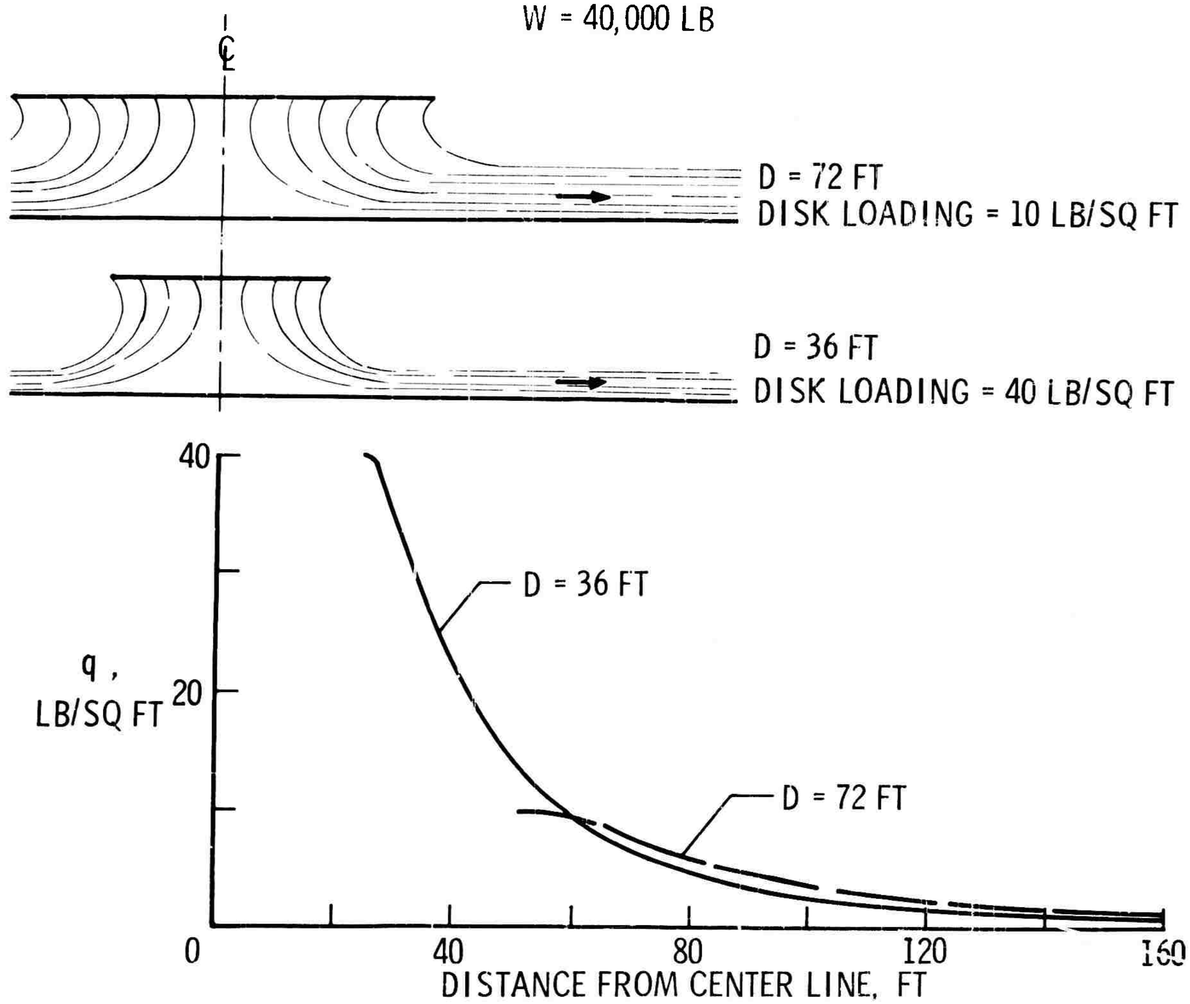
CURTISS–WRIGHT X–100 AIRCRAFT



NASA

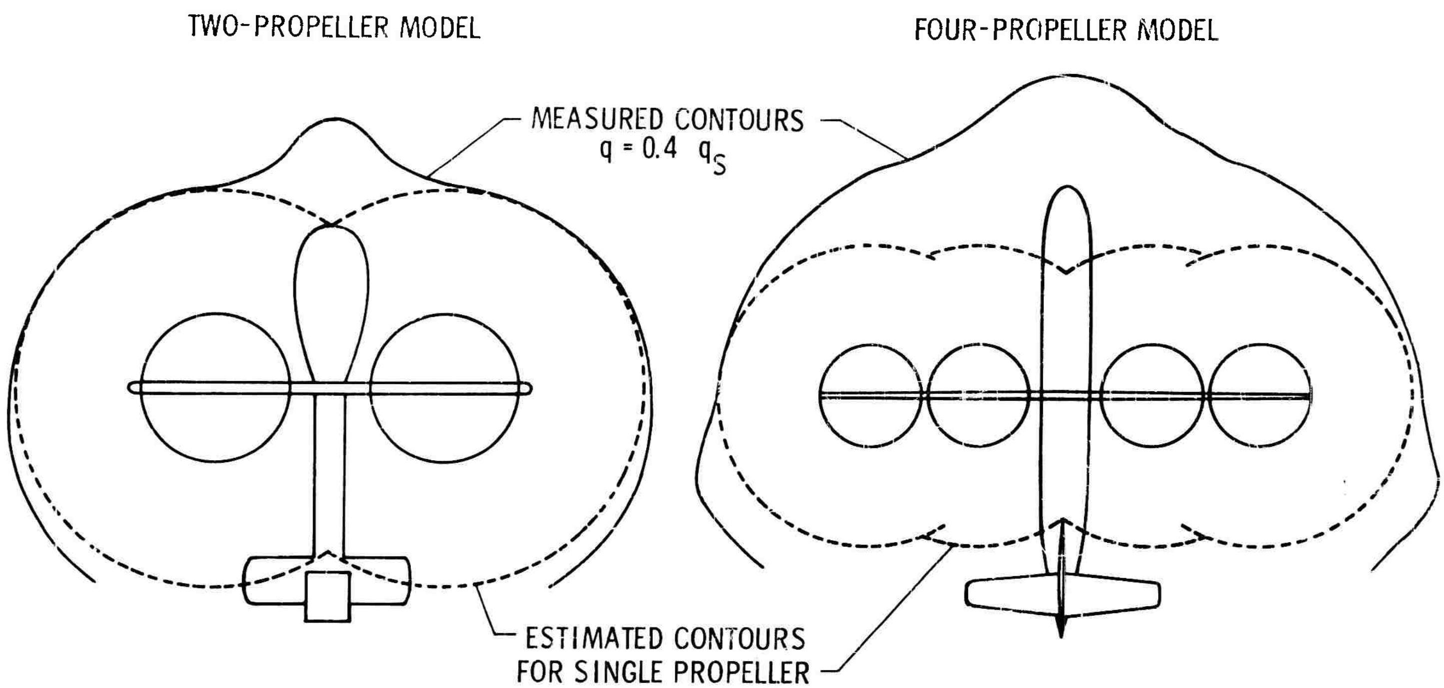
SLIPSTREAM DECAY FOR TWO DISK LOADINGS

W = 40,000 LB



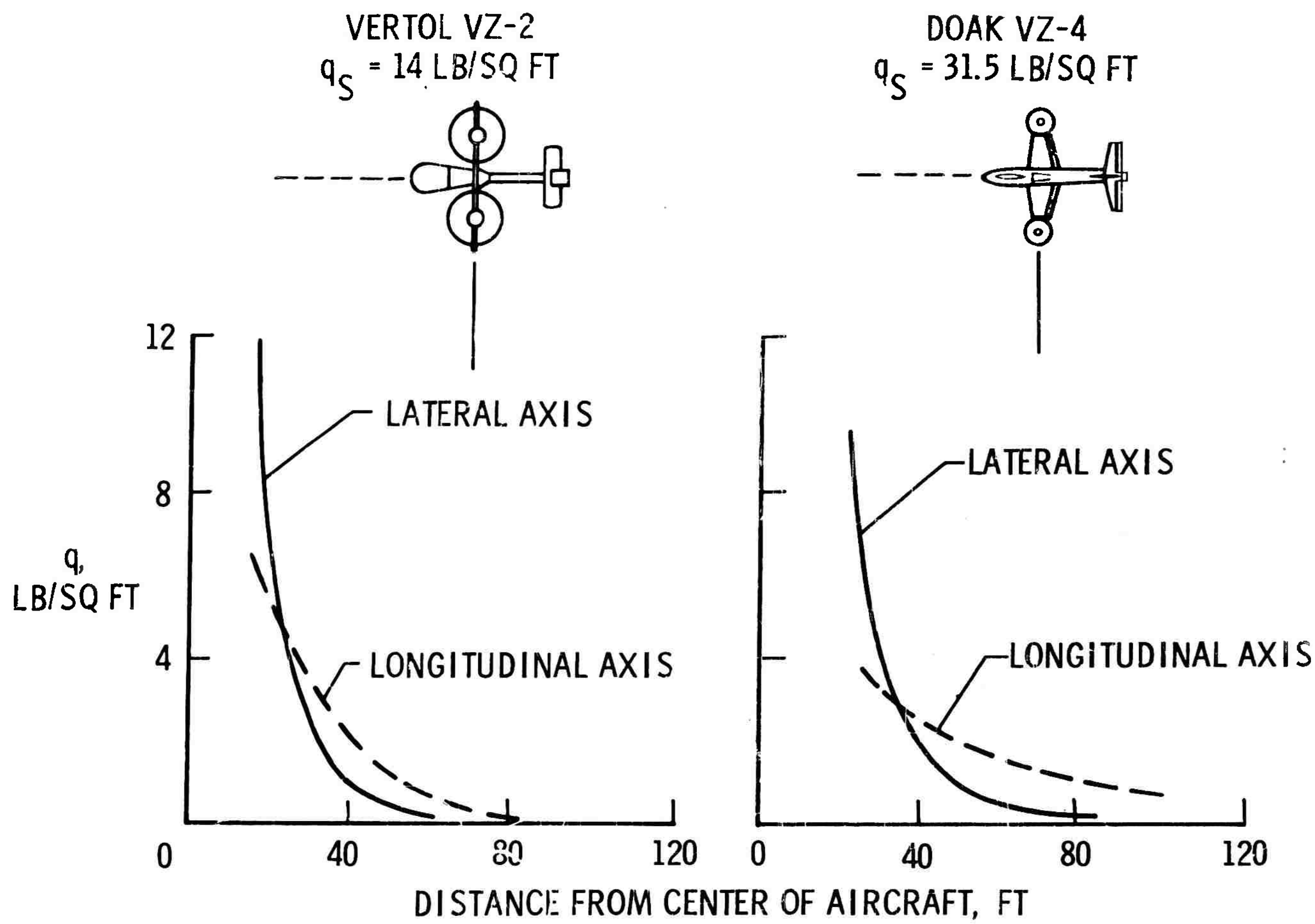
NASA

GROUND DYNAMIC PRESSURE CONTOURS
FOR $q = 0.4$ SLIPSTREAM q



NASA

DYNAMIC PRESSURE ALONG THE GROUND



NASA

PAPER NO. 8

PARTICLE MOVEMENT AND VELOCITY SURVEY TESTS CONDUCTED BY HILLER AIRCRAFT WITH VARIOUS VTOL AND GEM PROPULSION DEVICES

by

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PARTICLE MOVEMENT AND VELOCITY SURVEY TESTS CONDUCTED BY HILLER AIRCRAFT WITH VARIOUS VTOL AND GEM PROPULSION DEVICES

The information which I am about to present is the result of two and one-half years' work on the VTOL Downwash Impingement Study contract DA 44-177-TC-500 and DA 44-177-TC-655, awarded Hiller Aircraft by the United States Army Transportation Research Command.

A mobile test rig was assembled on a 5-ton U. S. Army 6 x 6 cargo truck (Figure 1 - Truck Test Rig). A Ford Model 332 industrial V-8 engine driving through a gearbox and 90° drive supplied the propulsion power. The entire propulsion unit was raised and lowered, by means of the truck winch, to vary the height above the ground. The impingement angle could be varied by rotating the 90° drive gearbox about the input shaft.

To provide the necessary air flow five-foot-diameter fixed pitch propellers and a two-foot-diameter six-bladed adjustable pitch ducted propeller (Figure 2) were used. The ducted propeller was fitted with a diffuser which provided an elongated exit area of approximately 6 sq. ft. area. A diffuser adapter (Figure 3) with two one-foot-diameter ducts was used to determine the mutual interference between the two air sources.

Two ground effect machines (GEM) configurations were simulated, a plenum chamber type GEM was provided for by the open end diffuser and an annular nozzle adapter was fitted to the diffuser. This adapter had a .6 inch air nozzle surrounding a 5.2 sq. ft. base plate. The nozzle directed the flow toward the base plate an angle of 45 degrees.

Initial tests were performed to determine the flow pattern and the surface velocity produced by a given configuration operating under specified loading conditions. The machine was operated over a non-eroding surface. Groups of pitot static tubes were located at several radial stations, each group provided a velocity profile. In addition a two-foot high movable rake with 22 total tubes was used (Figure 4). This rake also mounted 5 weathervane type pitot tubes spaced within the two-foot height. Splitter plates were located normal to the surface and along a radial line. They were used to mount tufts. These splitter plates (or tuft boards) were divided into six-inch squares, in the center of each square a tuft was attached. The tuft boards proved quite valuable in evaluating the flow field. Photographs of the tuft boards revealed that the air jet issuing from the duct or propeller (Figure 5) turns an extremely sharp corner issuing out radially in a very thin layer (Figure 6). The exit flow moves out along the surface and shows no tendency to flow back into the duct inlet (Figure 7).

This is apparently true even at high impingement angles with the surface. Aligning the tuft boards with the wind and orientating the ducted propeller on the upwind and downwind side of the boards, the exit flow pattern as influenced by a free stream velocity was obtained. As was suspected during earlier test, the wind has a very pronounced influence on the flow pattern. Due to the rapid decay in the surface dynamic pressure with radial distance, a low velocity wind will stop the outward flow at relatively low values of x/R on the upwind side (Figure 8). It would appear that the shearing forces, due to the high relative velocity between the two flows causes the surface layer to roll up and be swept back toward the source. The flow pattern on the downwind side is relatively unchanged.(Figure 9). Note that the first few rows of tufts indicate that the flow is nearly parallel to the jet.

The data obtained from the velocity profile tests was plotted using heights above the surface in terms of diameters (h/D) against the measured dynamic pressure to exit dynamic pressure ratio (q/qm) Figure 10. These curves were found to be independent of disk loading. The maximum dynamic pressure from these curves was cross plotted against the radial distance to obtain the maximum dynamic pressure variation with radial location (x/R). (Figure 11). The maximum value (q/qm) from the x/R curves is the maximum value regardless of height or radial location, and it is therefore called the field maximum dynamic pressure ratio (q/qm) Max. field. This field maximum (q/qm) was then plotted versus (Z/D) (Figure 12) to determine the influence of exit height above the surface. The surface velocity was found to increase rapidly as Z/D was reduced below one.

The surface dynamic pressure profiles and the maximum values obtained were found to correlate well with other published data, and data obtained from an 8-foot platform and an H-23C helicopter. Calculations based on the momentum theory, assuming no losses, were made, the resulting maximum surface dynamic pressures were in the order of 20 percent greater than those obtained in tests of the ducted propeller and the two GEM configurations.

After completion of the velocity survey tests the equipment was shipped to Vicksburg, Mississippi where the U. S. Army Engineers Waterways Experiment Station provided test sites, soils analysis, and other valuable assistance. The two-foot duct, the side by side ducts and the two GEM configurations were tested over various soils with different surface preparations. The data obtained included: the quantity of material trapped at various locations in the flow field during timed tests, measurements of the eroded area, continuous records of the surface elevation during water tests, and considerable film coverage.

All configurations exhibited similar characteristics. At the beginning of the test the flow spread out along the surface, when the surface suffered considerable erosion the flow was projected nearly vertical. The side by side ducts have a secondary impingement which takes place midway between the two ducts. After the initial impingement with the surface the radial surface flows again impinge upon each other causing a greater mass flow (of the same velocity) out along the minor axis of the twin duct system. A test of the side by side ducts over dry sand was repeated with one duct diverted. The eroded section caused by one of the paired ducts was of the same shape and size as that produced by the single duct, and the total test time to produce the vertical flow projection was the same. The annular nozzle GEM produced greater vertical projection of soils and spray than did any other configuration.

Although tests were conducted during periods when the surface wind was five miles per hour or less, the influence of the surface wind is such to cause considerable recirculation of light dust particles. This slide (Figure 13) shows the two-foot duct in operation over plowed lean clay during a period of almost complete calm. A similar test (Figure 14) was conducted during a 3 to 5 mile per hour surface wind. The rolling up of the surface flow, and the return of the dust cloud over the equipment can be seen.

An example of the extent to which the light dust was projected into the air (Figure 15) is shown by this slide. During tests of the two-foot duct over river gravel at high disk loading and low Z/D the propeller blades suffered extensive damage.

The ingestion of material into the inlet could be eliminated by tilting the duct; however, it was found that very large angles were required and surface winds could blow the light material back to the inlet (Figure 16). This slide shows the two-foot duct at 140 lb. per sq. ft. over the water test site. A close up of the duct inlet at 30 degrees is shown in the next slide. (Figure 17). Note that the ingestion is greatly retarded by the presence of the screen. The spray heights obtained in these tests compare reasonably well with NASA data (Figure 18). The surface dynamic pressure for the two-foot duct are calculated values assuming no losses and are therefore approximately 20 percent high.

A short film will precede the conclusions and it will help to bring out some of the points I have mentioned.

In general the light material will become airborne under the downwash of the lowest disk loading equipment. All types of binding material, water, compacting, or vegetation help to retard the erosion. Aircraft utilizing highly loaded propellers or ducted propellers will either

have to choose landing sites carefully or be protected from damage by airborne particles. Engines and bearings can be protected by some means of filteration but pilot visibility could be greatly impaired by the fine dust cloud.

Small prepared sites are feasible, although the two-foot duct produced considerable dust when operated over a 30 ft. square mat (the mat used for the film was 50 ft. square). The tests over the tall grass showed that the surface flow could be deflected above the surface quite simply.

One of the most demanding problems at the present time is that associated with sea rescue where highly loaded VTOL aircraft, operating in ground effect, although capable of arriving at the scene early, would surely drown any disaster victim.

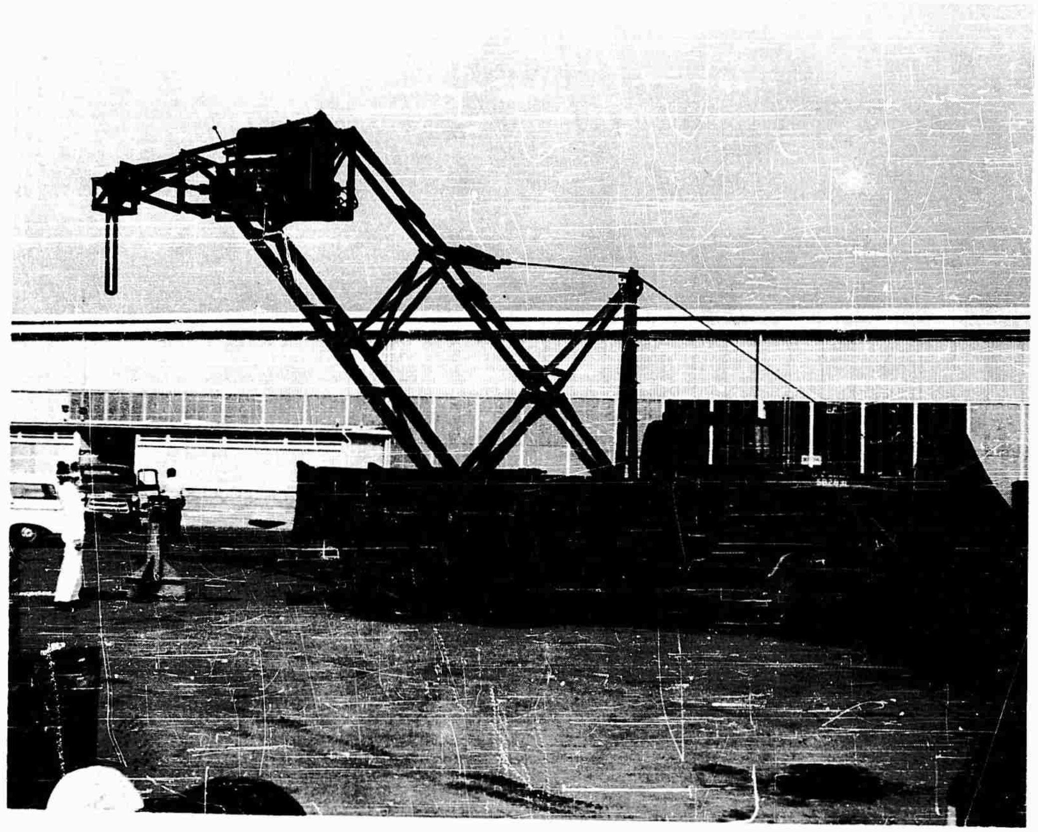


FIG. 1. TRUCK TEST RIG

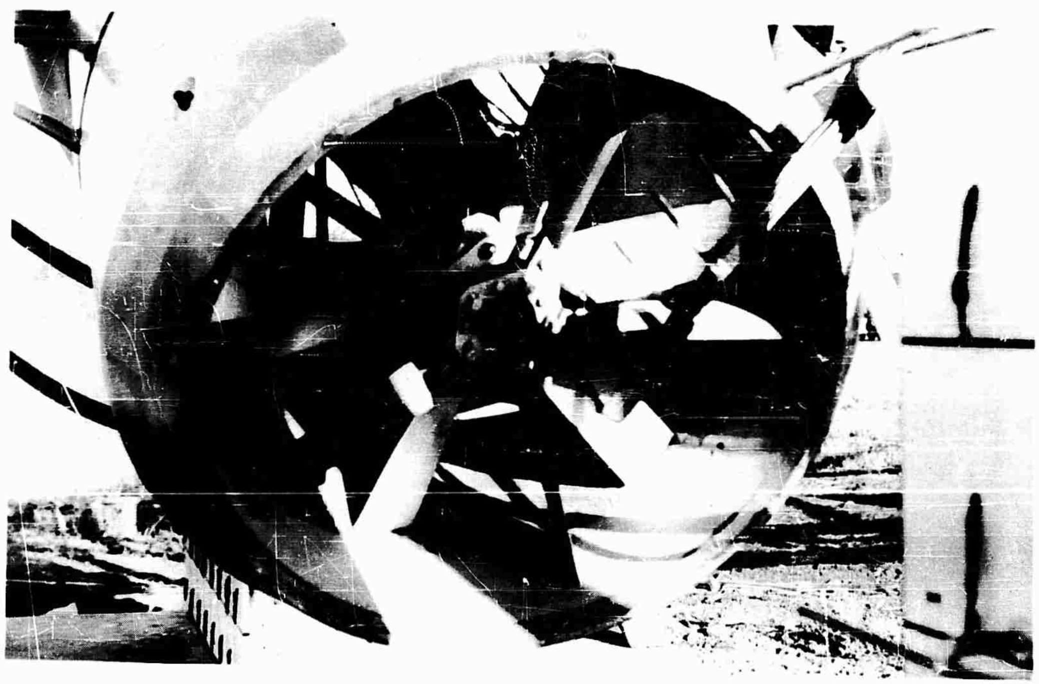
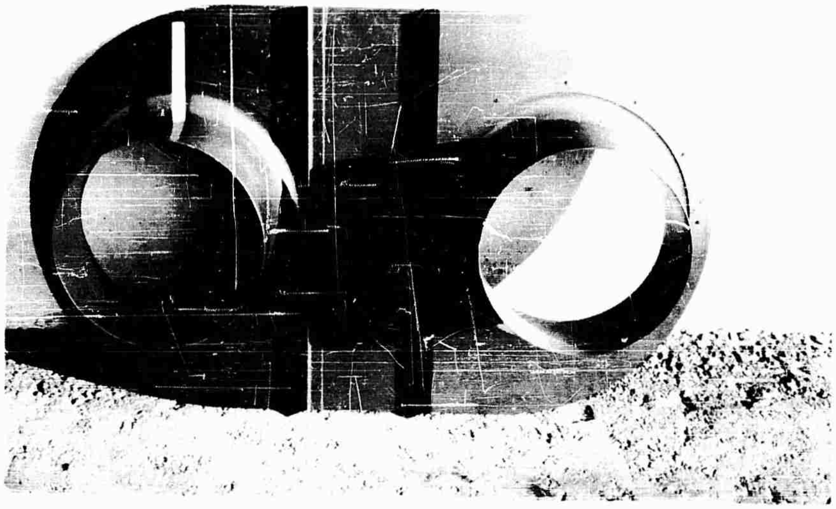
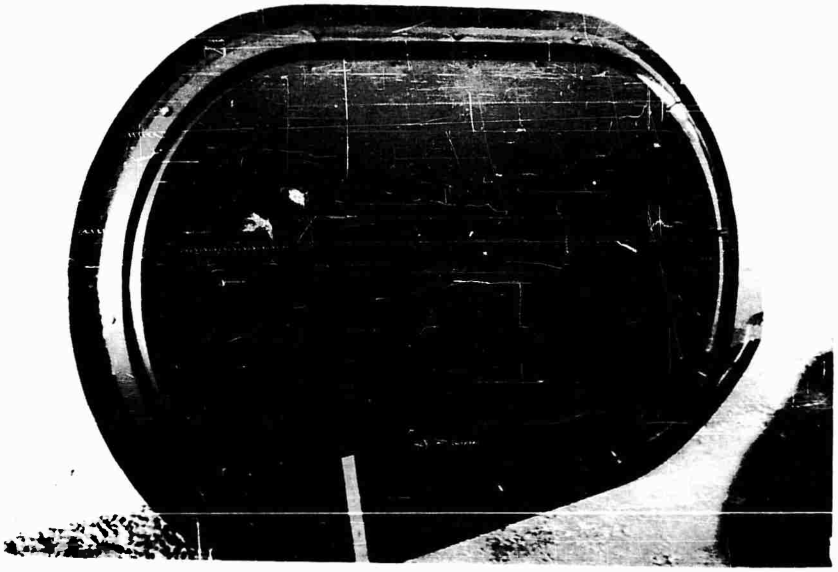


FIG. 2. DUCTED FAN ASSEMBLY



SIDE BY SIDE FLOW ADAPTER



ANNULAR NOZZLE FLOW ADAPTER

FIGURE 3

FIG. 4 5-FOOT DIAMETER PROPELLER
AXIS INCLINATION 30 DEGREES

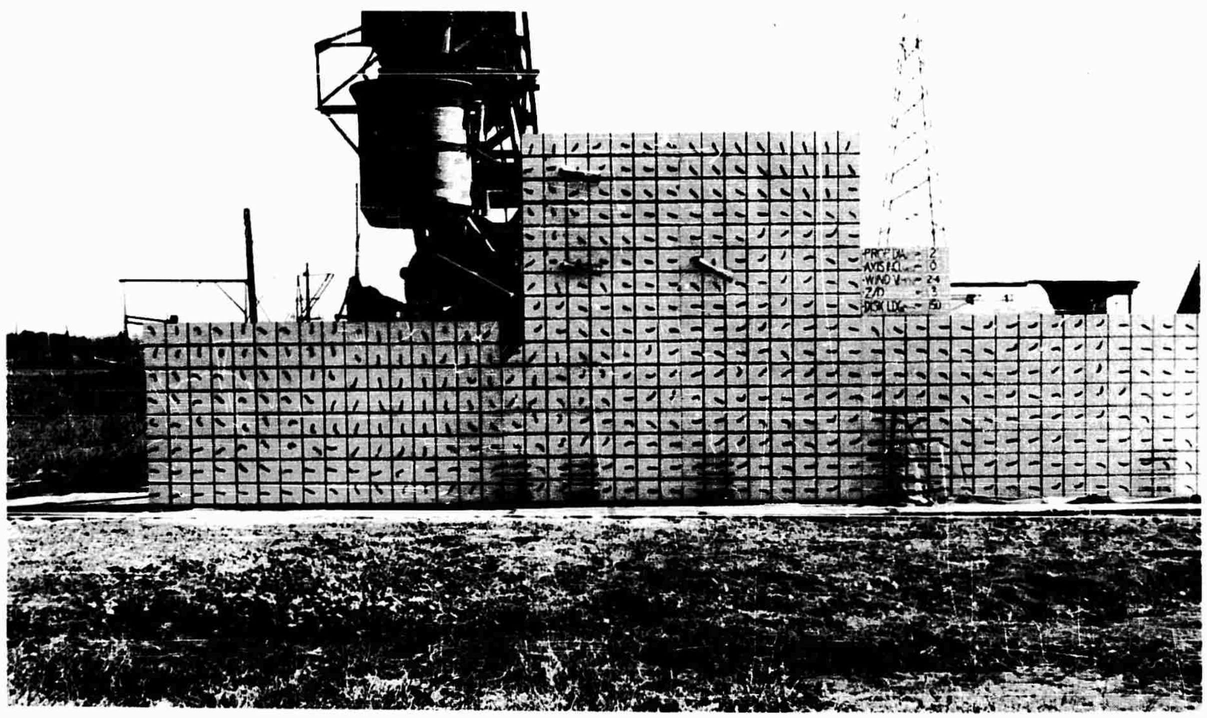
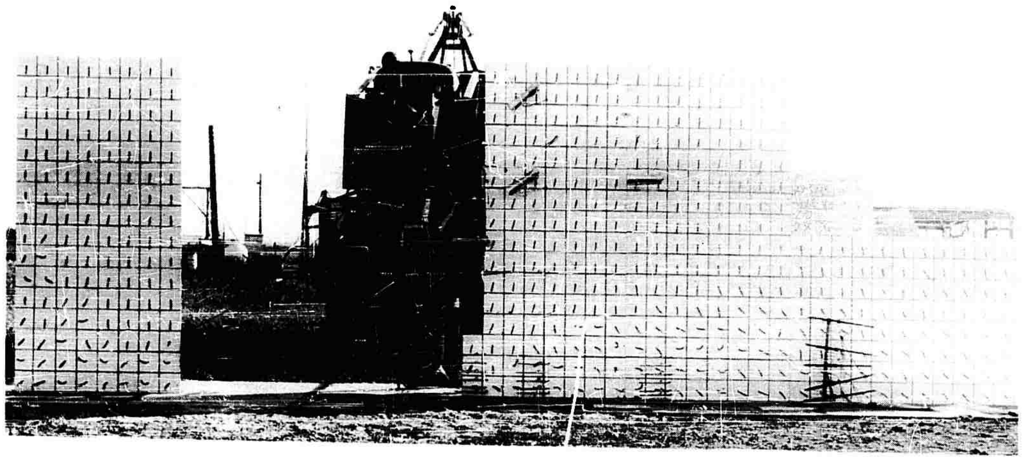
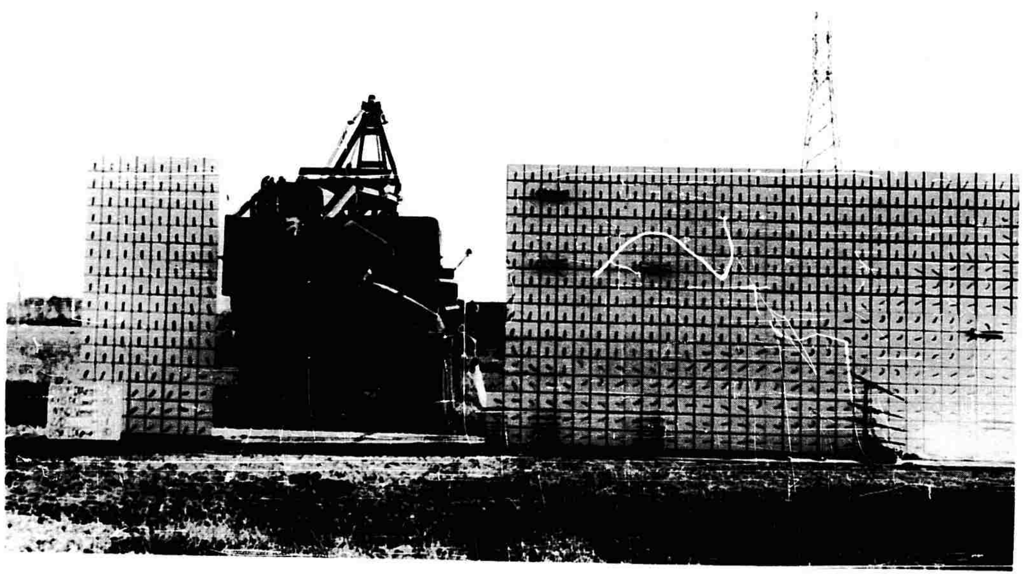


FIG. 5 TUFT BOARDS, PANEL HORIZONTAL



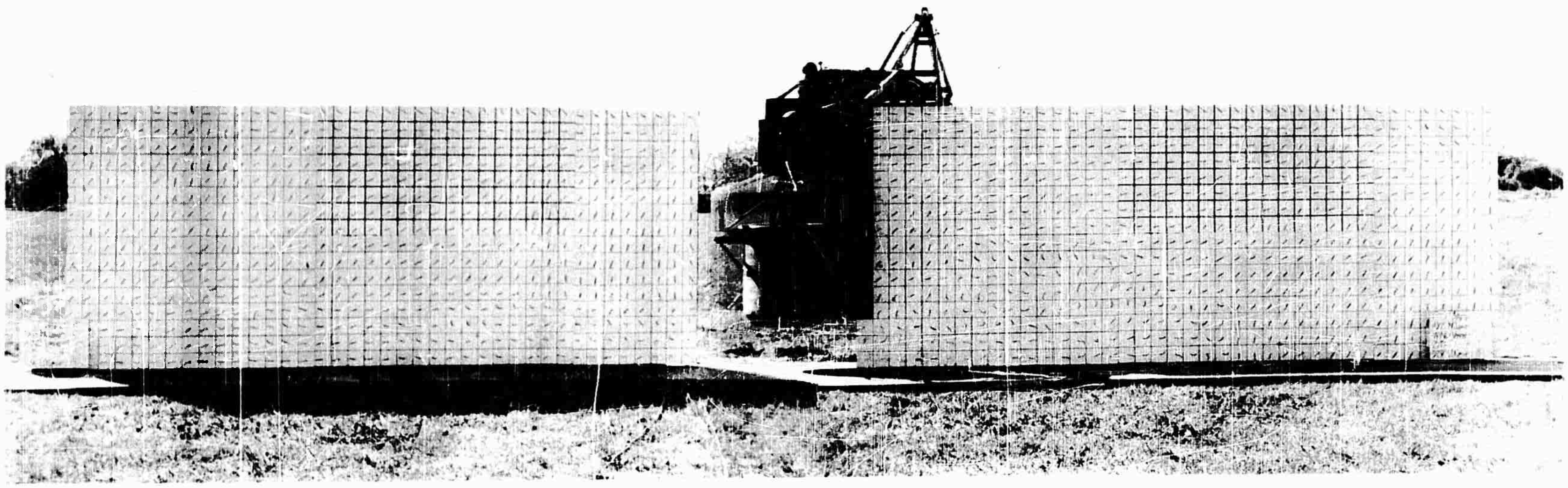
DISK LOADING = 15.4 LBS./SQ.FT.

Fig. 6



DISK LOADING = 30 LBS./SQ.FT.

FIG. 7



DISK LOADING 80 LBS./SQ.FT.

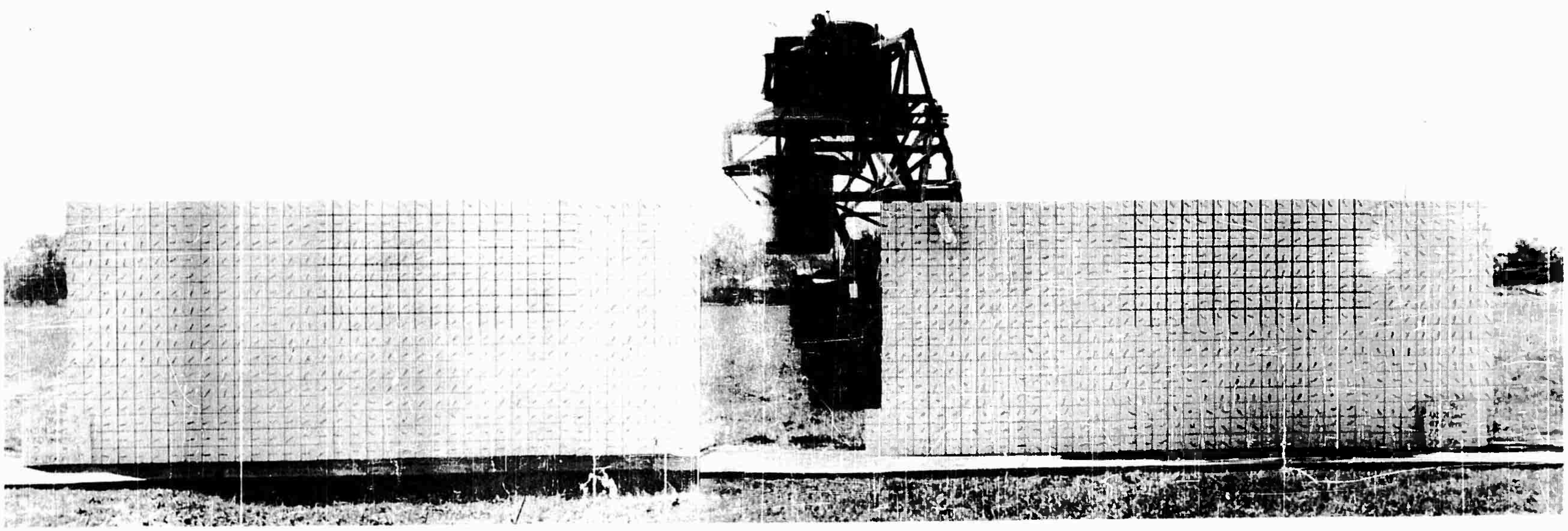


FIG. 8. FIG. 9. TUFT BOARD FLOW PATTERNS, DUCTED FAN, 10 TO 15 MPH WIND, DISK LOADING 120 LBS./SQ.FT.

PREPARED	NAME: A. Morse	DATE: 2-8-60	HILLER HELICOPTERS	PAGE
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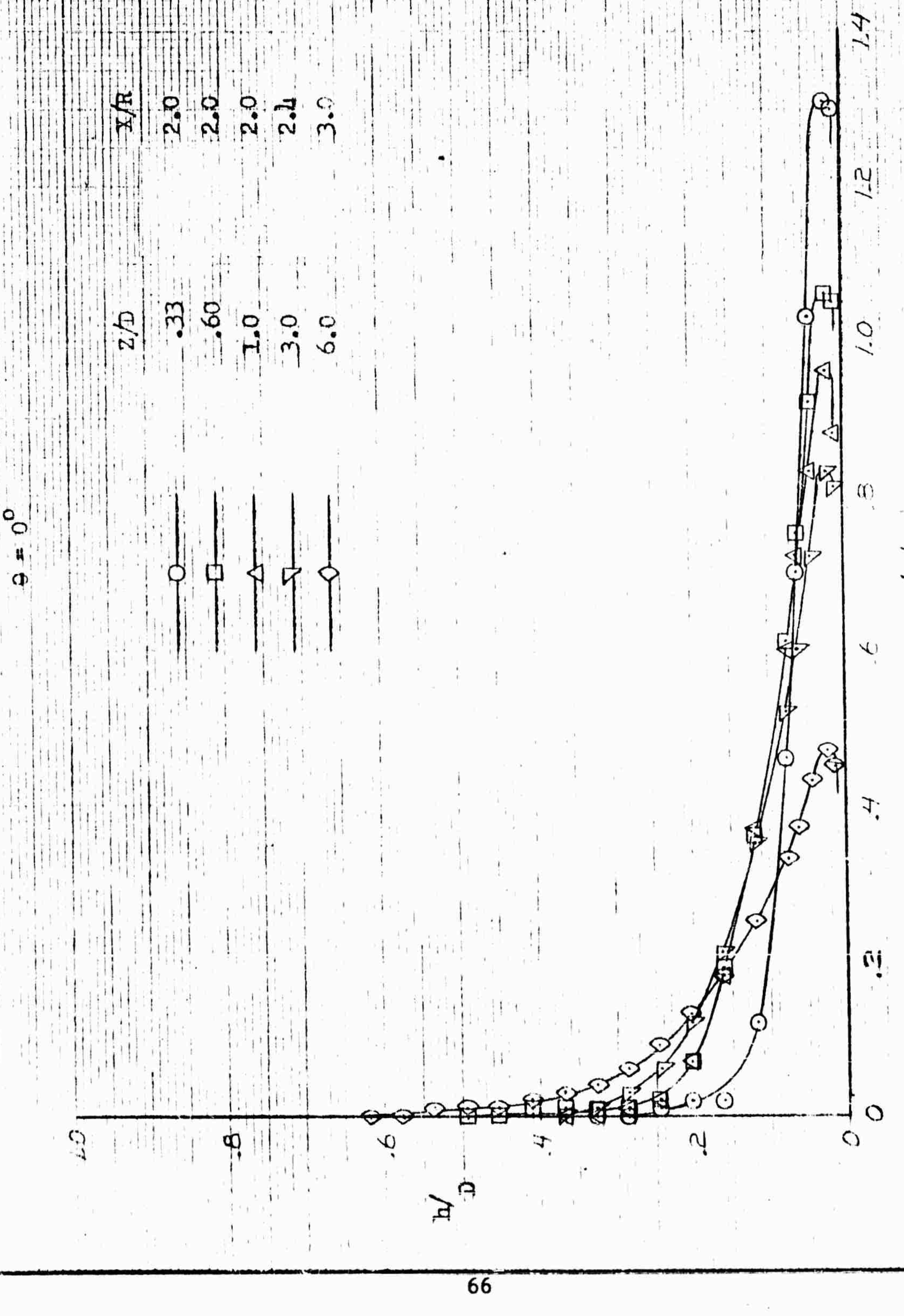
APPROVED				REPORT NO. 60-15

Fig. 20 - TYPICAL DYNAMIC HEAD PROFILES

$\theta = 0^{\circ}$



PREPARED	NAME A. Morse	DATE ?-8-60	HILLER HELICOPTERS	PAGE
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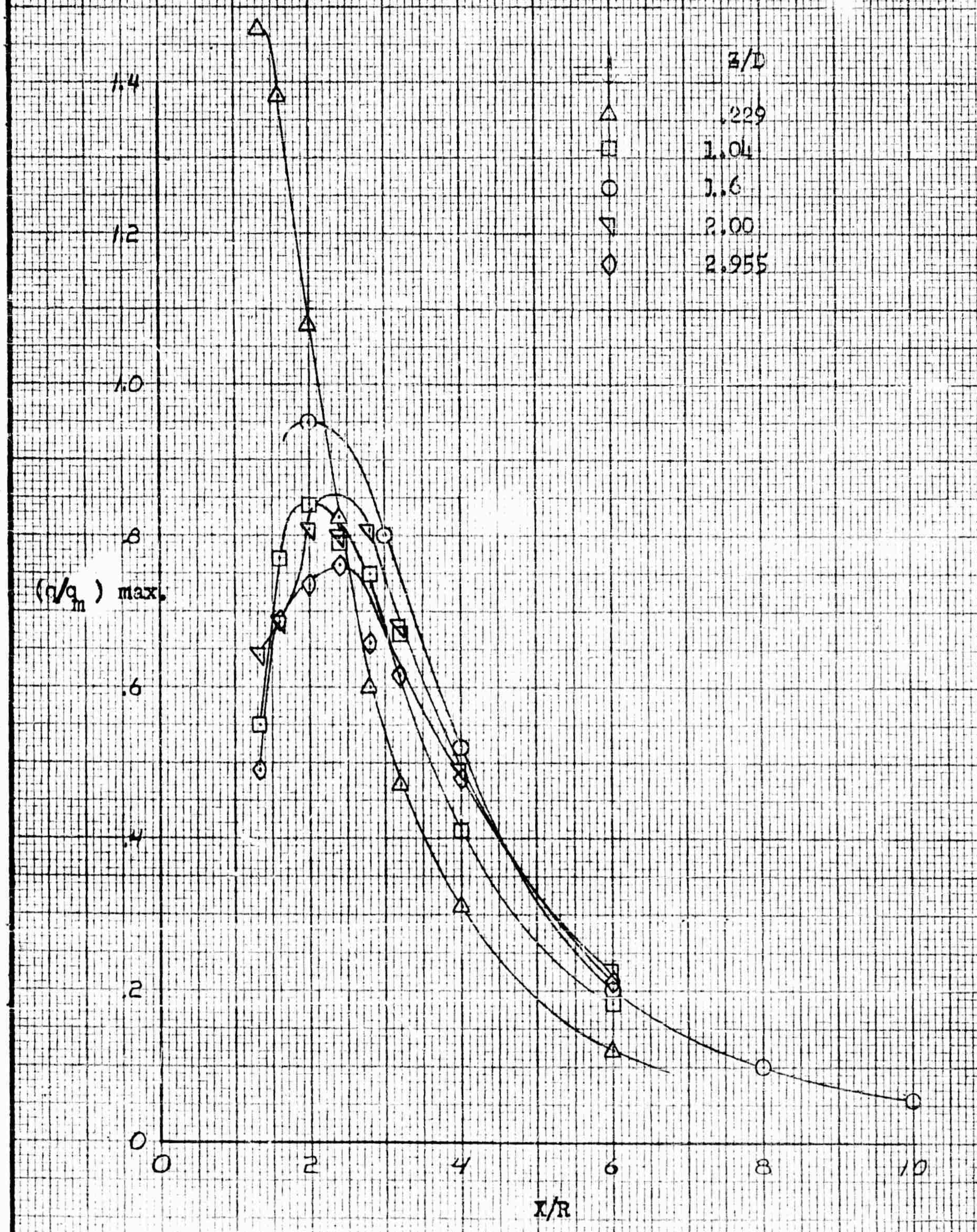
APPROVED				REPORT NO. 60-15

Fig. 21 - VARIATION OF (q/q_m) MAXIMUM WITH X/R

2.0-FT. DIAMETER DUCT

$\theta = 0°$



E-128

PREPARED	NAME A. Morse	DATE 2-8-60	HILLER HELICOPTERS	PAGE 15
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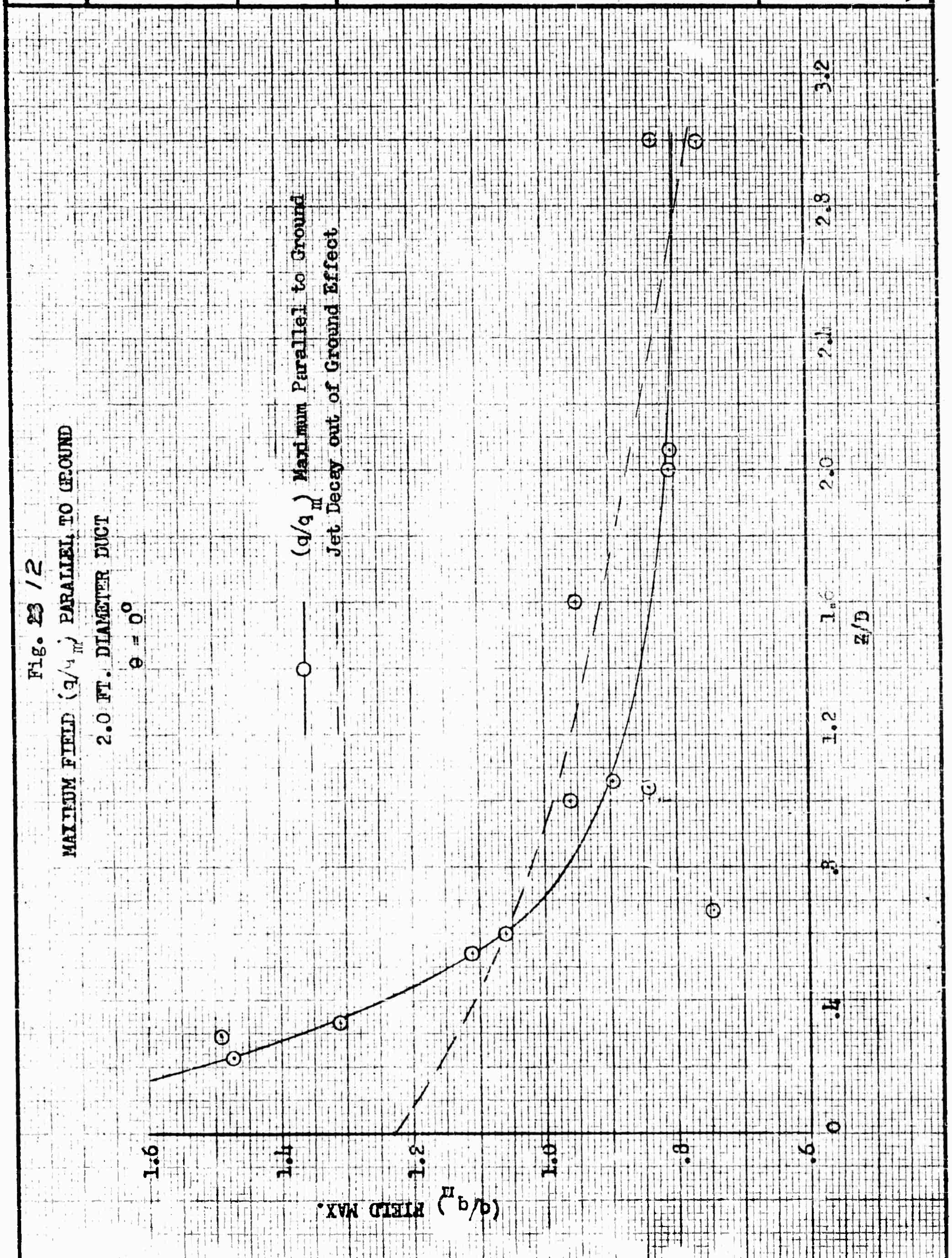
APPROVED				REPORT NO. 60-15



E-12E

Fig. 13 Test III-A108
During Operation

Figure 14 Test I-B15
During Operation

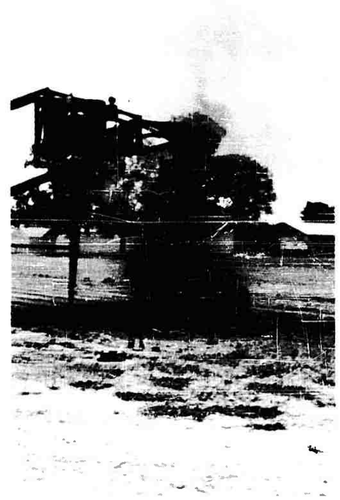


FIGURE 15

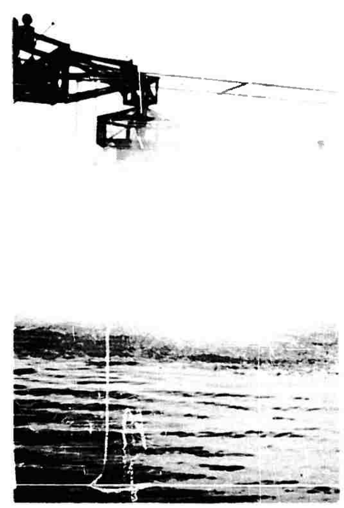


FIGURE 16

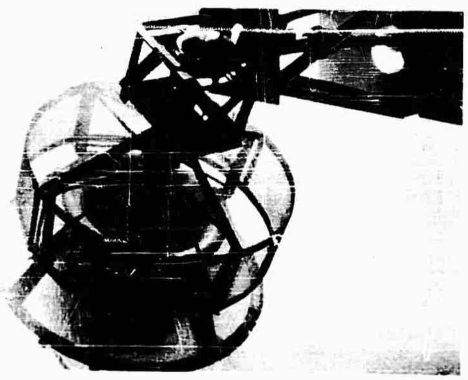


Fig. 17. Test V-A49
During Operation

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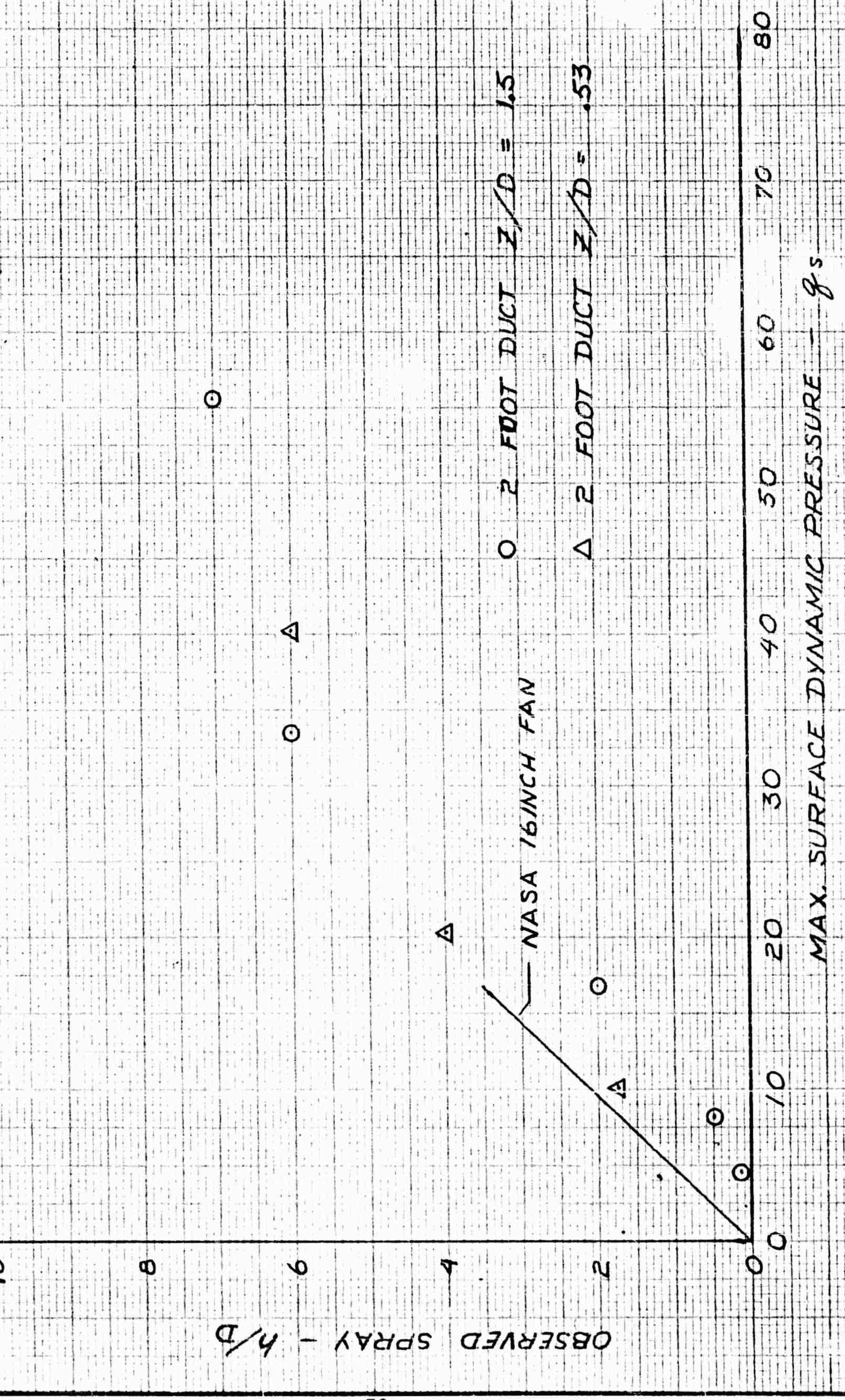
FIG 18

HEIGHT AT WHICH SPRAY WAS OBSERVED FOR VARIOUS SURFACE DYNAMIC PRESSURES



PAPER NO. 9

KELLETT FULL-SCALE DOWNWASH IMPINGEMENT EXPERIMENTAL INVESTIGATION

by

Mr. Leonard Goland
Vice President, Research and Development
Kellett Aircraft Corporation
Willow Grove, Pennsylvania

FULL-SCALE DOWNWASH IMPINGEMENT EXPERIMENTAL INVESTIGATION

The downwash impingement investigation being conducted by the Kellett Aircraft Corporation is jointly funded by the Army and Navy under Contract No. NOw 60-0450-f. The project is under the direction of Mr. Ben Stein, Bureau of Naval Weapons.

The overall objective of the program is to determine full scale effects of rotor downwash on terrain, equipment, personnel, and on take-off-and-landing procedures.

First of all, I would like to indicate how this program arose. It appeared that there was some noteworthy work being done using the small scale models, and certainly a great deal of information can be abstracted from this work; however, there was a dearth of full scale data. In addition, there was a need to use the actual terrain; that is, to test over existing "as is" terrain. I think that, considering the number of variables in this problem, an attempt to solve the problem solely by analytical or semi-empirical methods would prove extremely difficult.

I would now like to give a description of the apparatus that we are going to use to study the impingement problem. The ideal test equipment would be the actual VTOL aircraft; however, this would be very expensive and it would involve a great deal of danger, and only limited data could be obtained. The next best apparatus appears to be a full size propeller and engine combination mounted on the end of a boom and perform the test by moving the crane to the actual terrain to be tested.

Slide #1 shows the test apparatus which consists of a 20 ton Bay City crane, a Pratt and Whitney 4360 engine and a Hamilton Standard 15' diameter propeller. The engine-propeller will generate approximately 10,500 pounds of thrust.

Slide #2 shows the propeller axis in a tilted position. Tests will be performed with the propeller tilted at an angle of 30 degrees. Notice the oil coolers projecting on either side of the engine in the air stream. Mounting the engine vertically caused some problems, but Pratt and Whitney Aircraft was extremely cooperative in helping to solve these problems. All forces and moments have been checked and we do not anticipate any trouble from static forces.

Slide #3 is a close-up which shows an oil cooler, and on the right is the air intake to the carburetor. A certain amount of operational problems are anticipated due to the downwash impingement on the terrain, but this is essentially the purpose of the program. That is to say, debris and dirt will be ingested into the engine causing maintenance problems, and debris and dirt will erode the propeller blades.

The maximum disc loadings that will be investigated will be in the neighborhood of approximately 60 pounds per square foot, and the program will be conducted by starting with 10 pounds per square foot, proceeding to 30 pounds per square foot, and then to 60 pounds per square foot. Actually, in ground effect, much higher values can be attained; however, even to achieve 60 pounds per square foot under certain terrain conditions may be difficult. This 60 pounds per square foot is equivalent to an out of ground effect downwash velocity of roughly 130 knots.

Nine different terrain conditions will be tested including snow and different kinds of sod and earth. Various propeller heights above the ground and various tilt angles will also be tested as mentioned previously. The important thing is that terrain in the "as is" condition will be subjected to these tests. The facilities at the Willow Grove Naval Air Station will be used, and tests will be performed on the runways. The positions of various objects, such as stones, will be noted. Additional objects will be placed in the downwash. For example, oil drums, various crates of equipment, and various structures will be placed nearby to see what happens to these objects at various disc loadings. One method for solution of the subject problem is to make a statistical survey of allowable operating conditions; the other method of solution is to devise means to alleviate the problem.

Data to be obtained in the present program will be measurements of the characteristics of the airflow, the effects of the air-flow on various types of terrain, the effects on the test rig itself, the effects on the materiel distributed around the test rig, and the effects on personnel. We are planning to start testing in a week or two and I hope I can present some of this test data at a future symposium. We expect that it will take us about 8 weeks to complete the program.

Additional aspects that we expect to investigate are:

a. Twin propeller testing (Slide #4). The same engine-propeller combination, in combination with a reflection plane can be used to get the solution to the twin propeller problem. As you know, when using twin propellers, the downwash effect is aggravated insofar as increased velocity arise in the plane of symmetry. This study can be conveniently accomplished with the existing equipment.

b. The effects of forward motion on the downwash problem will also be studies. The crane can be driven at speeds up to 30 knots to get conditions other than hovering over the terrain.

c. A great deal of time will be spent and presently is being spent in solving this problem. I don't think the problem is something that is unsolvable; we have certainly solved more complicated problems. There have been numerous statements made that we will have to limit the disc loadings of these V/STOL aircraft to ten pounds per square foot, 15 pounds per square foot, et cetera. I think that this is merely avoiding the problem. Solutions to this

problem can be obtained, and we will have excellent aircraft in the future operating at the higher disc loadings.

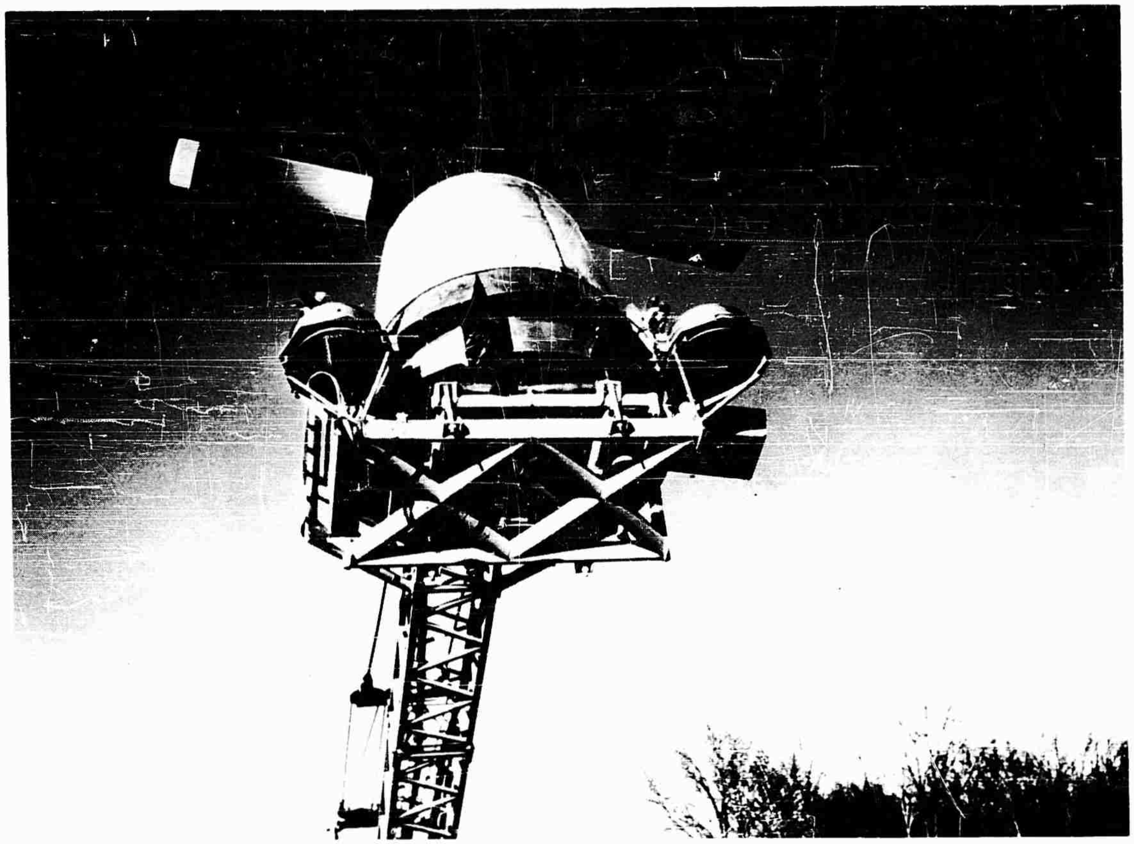
Certainly we do not feel that we have hit upon the solution as yet, but I will give you some indication of our progress and of some of the devices we are thinking about. (Slide #5). These devices are not necessarily novel; slide #5 shows a terrain cover that could be dropped from the aircraft. It includes some type of air-bottle which will inflate a portion of this cover and thereby protect the terrain. This is a simple device and may be an answer. Certain problems having to do with the stability of the cover must be looked into, but we feel that a cover such as this can be made and if the weight penalty would not be large, such a cover could solve the problem. Many people have advocated as a possible solution to the problem terrain stabilization; this certainly should be studied and carried forward. Another scheme which our people have conceived is given on Slide #6, the airborne downwash deflector. Here again it's conceivable that a deflector can be attached to the engine propeller combination and deflect the downwash in such a manner that the loss in lift will not be excessive and still it can do much to diminish the effects of the downwash. It seems as though there is plenty of room here for some novel thinking as far as this type of solution is concerned.

Slide #7 shows a downwash diverter which is dropped with an air bottle; the diverter deflects the downwash so as to minimize the effects on terrain. Slide #8 is something similar, whereas a tublike arrangement changes the flow pattern and protects the terrain. Slide #9 is simply an elevated ground board, where the legs are inflated, essentially supporting a ground cover.

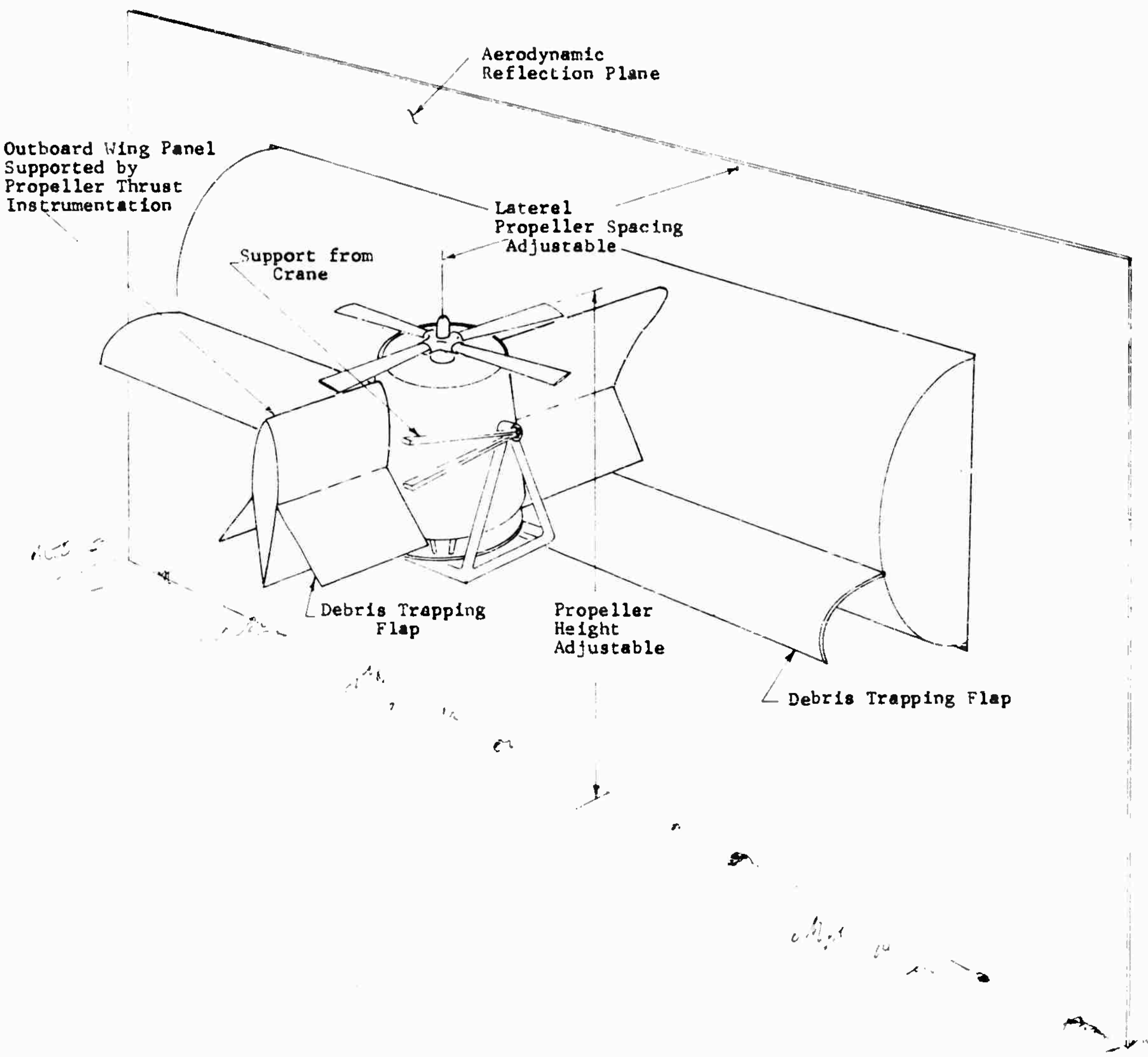
This represents our present thinking and philosophy of this research. We feel that due to the number of variables to be considered in this problem, the best approach to obtain answers for the immediate future is actually using full scale equipment that I have shown. We also feel that devices can be designed and developed that would alleviate this problem. We do not think that the problem in itself is insurmountable, but it will take some creative design work. In addition, if anybody has any other designs or concepts for solving this problem and if our device, our full scale rig can be of service to you, we shall be glad to make these available. Our main purpose, as with everybody here, is to solve the problem and I trust that at the next symposium we will have achieved a number of practical solutions.

Slide 1. Test Apparatus: A 20-Ton Bay City Crane, a Pratt and Whitney 4360 Engine, and a Hamilton Standard 15-Foot Diameter Propeller.

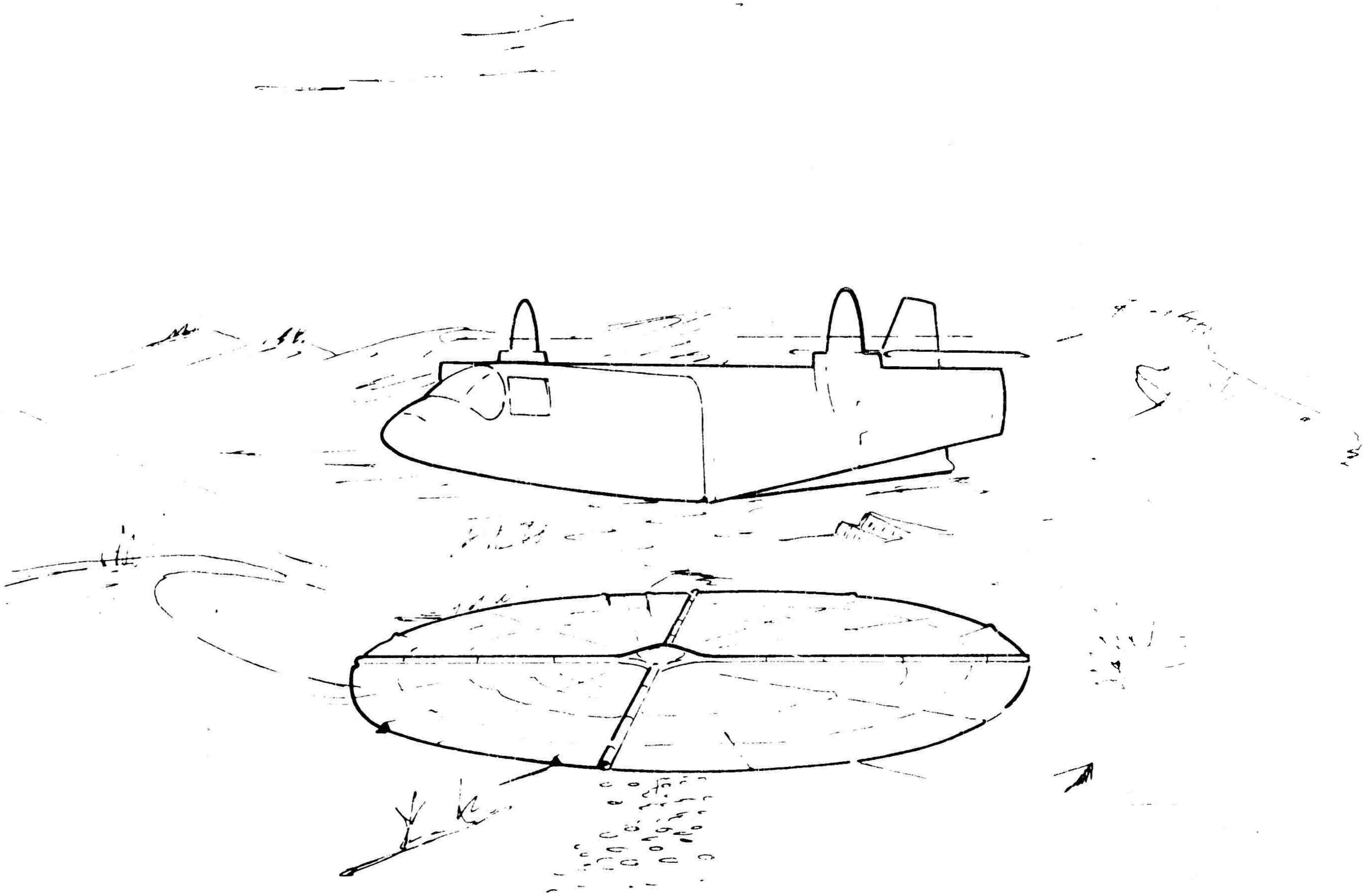
Slide 2. The Propeller Axis Shown in a Tilted Position.



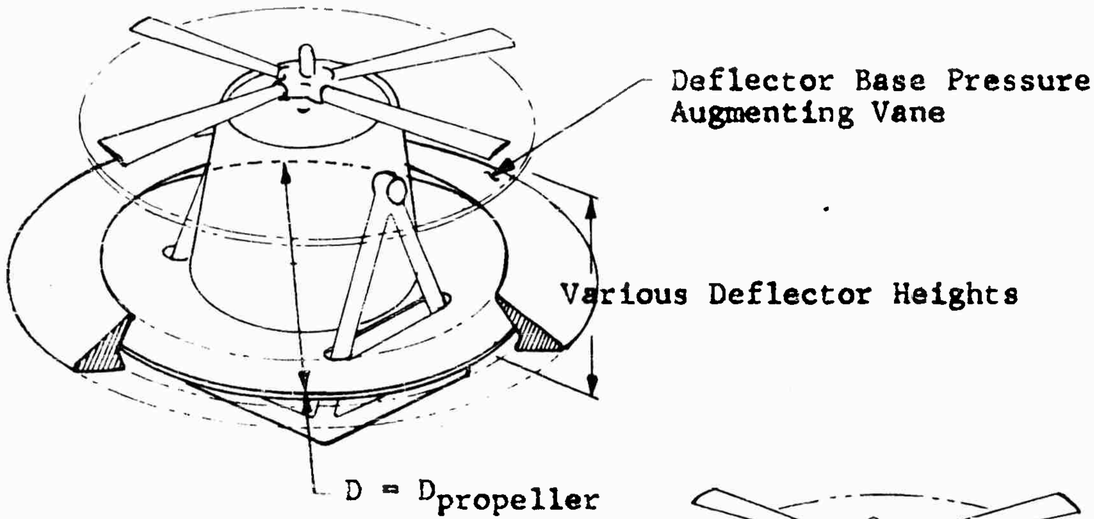
Slide 3. Propeller and Engine Arrangement.



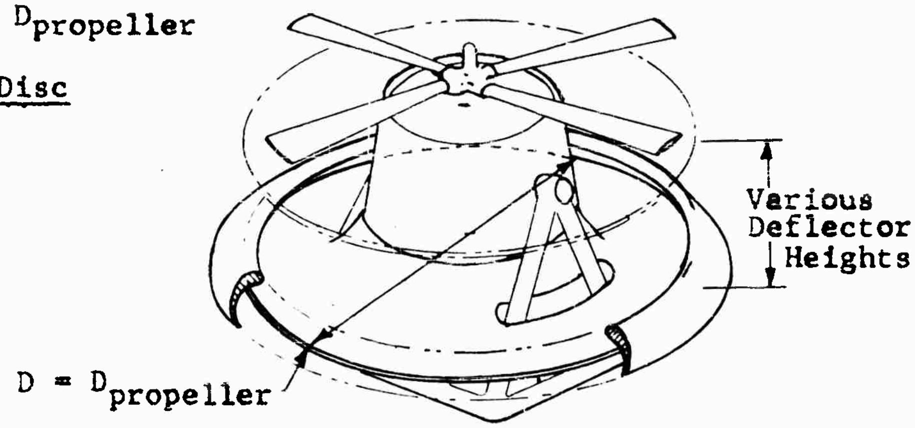
Slide 4. Test Rig, Twin Propeller VTOL Simulation for Terrain Disturbance Investigation.



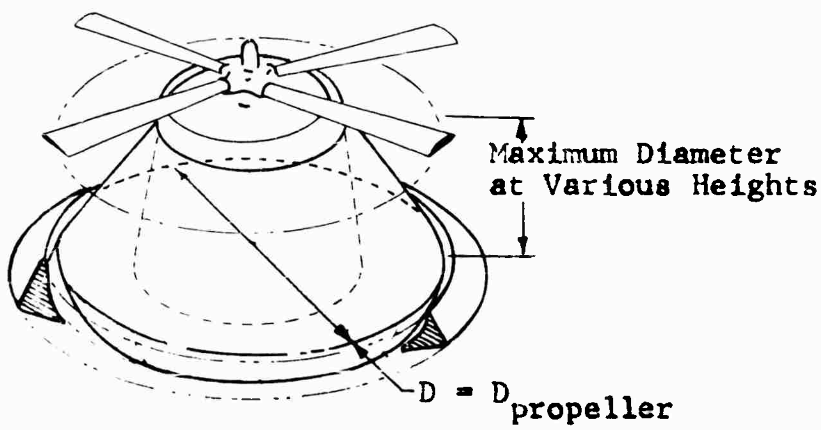
Slide 5. A Terrain Cover That Could Be Dropped From the Aircraft.



Large Deflector Disc

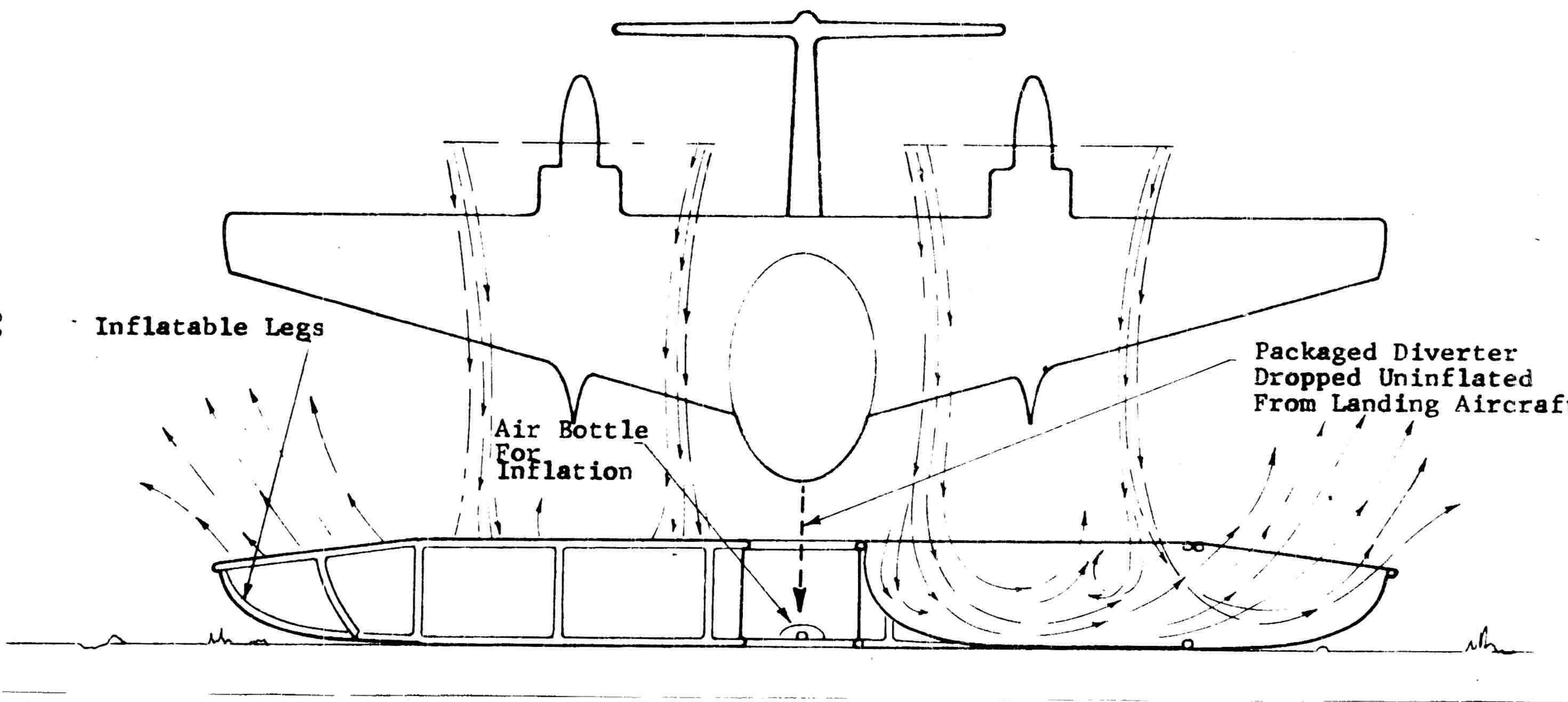


Curved Deflector Disc

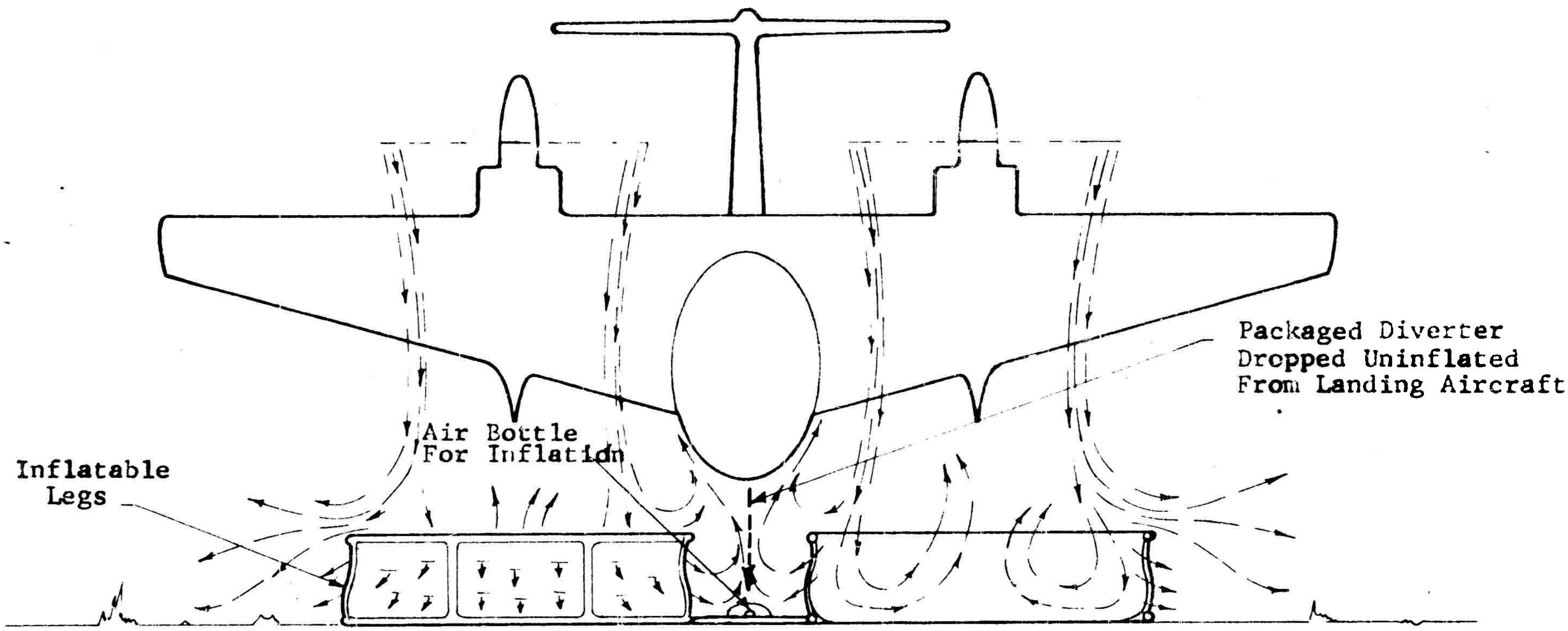


Large Volume Deflector

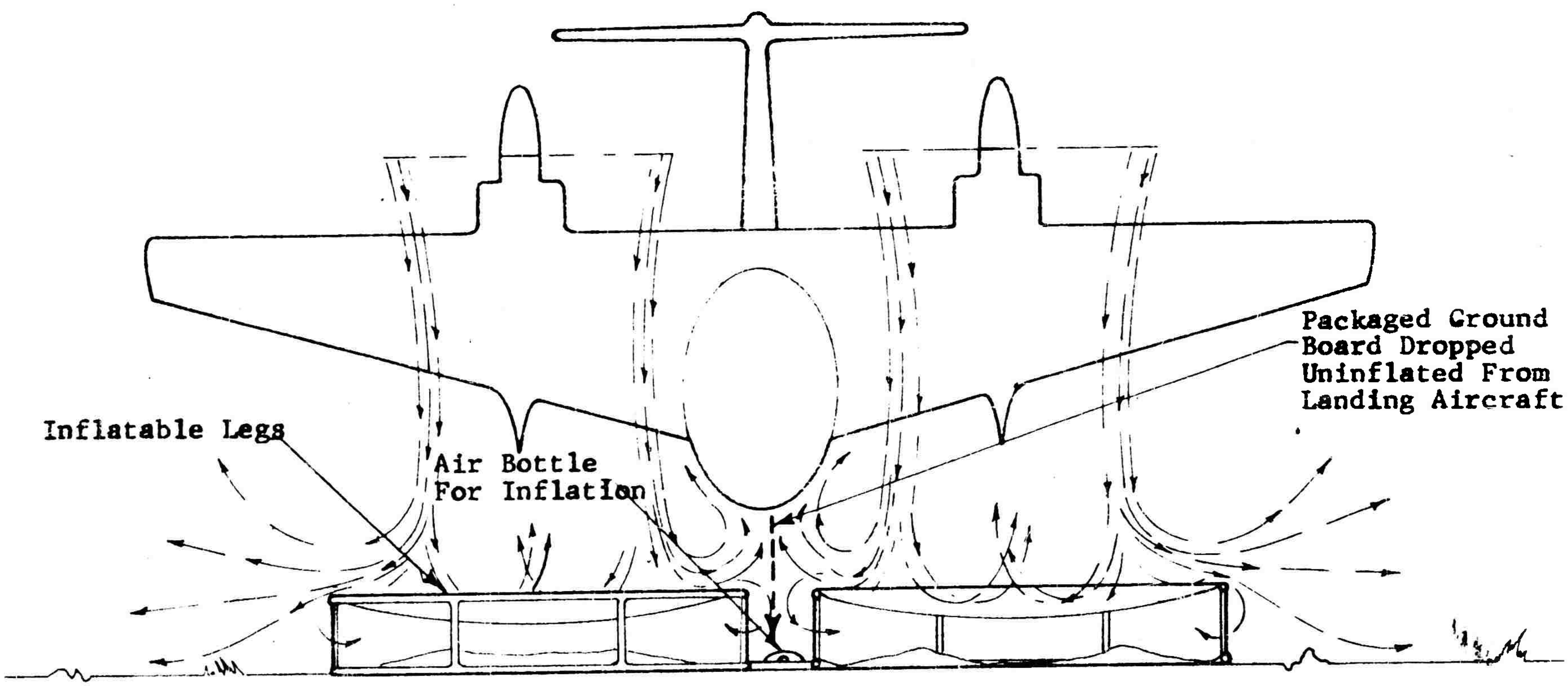
Slide 6. Test Rigs, Airborne Downwash Deflectors.



Slide 7. Downwash Redirecting Diverter.



Slide 8. Tub-Like Downwash Deflector.



Slide 9. Elevated Ground Board Downwash Deflector.

PAPER NO. 10

FACTORS INFLUENCING GROUND PARTICLE ENTRAINMENT

by

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FACTORS INFLUENCING GROUND PARTICLE ENTRAINMENT

The Cornell Aeronautical Laboratory has recently completed a review of the downwash impingement problem and the particle entrainment problem for the U. S. Army Transportation Research Command. The purpose of this review was to assess our present understanding of the aerodynamic processes which contribute to the entrainment of particles, and to consider some broad approaches which hold promise for ultimately solving the problem. The scope of this review was to include all STOL/VTOL configurations; however, reflecting the current industrial and research emphasis, primary consideration was given to those configurations which employed lifting propellers, rotors, and rotatable turbojets. Brief consideration was given to the jet flap and the deflected slipstream configuration, and they are discussed in the report on this study.

Our approach to the problem was based upon the viewpoint that a solution to the problem could follow only if we had a quantitative understanding of why the condition existed, that is, why the particles left the ground and why they were maintained in the air stream. In this study the available theories were used to predict the important aerodynamic effects occurring in the impinging jet, and these results were compared with the existing experimental data to quantitatively assess the present understanding.

The results indicate the qualitative understanding of the problem is good. It appears that all the important flow processes have been identified. However, the quantitative understanding is rather poor in most areas. On the basis of this study, a new mechanism for entraining the particles is proposed. That is, it is concluded that the aerodynamic forces on the particles are such that they can be lifted directly into the stream.

As illustrated in Figure 1, there are two general types of impinging jets. The upper sketch illustrates the important features of a jet formed by a rotor or propeller. First it is noted that load distribution is markedly nonuniform so that in hovering near the ground, a core of reverse flow is embedded within the jet. In addition, the flow is, in principle, nonsteady as indicated by the discrete spiral tip vortices being shed from the rotor. This nonuniform, unsteady slipstream impinges on the ground, flaring the jet boundary so that ultimately a radial ground flow is established including a viscous region at the ground--a ground boundary layer.

Now in contrast, consider a jet produced by an ideal turbojet engine, the second sketch in Figure 1. The initial distribution of velocities is rectangular and the jet flow is steady. In both this case and that for a propeller jet, if the configuration is far enough above the ground, viscous mixing will be important, and near the ground plane the distribution of velocities in the jet will be nonuniform. This nonuniform flow impinges upon the ground plane to produce flaring of the jet boundary, and again a radial ground flow is established with a viscous boundary layer on the ground plane.

At this juncture one can eliminate many of the details in the impinging jet on the basis of some elementary observations. In comparing the experimental distribution of velocities in the ground flow for an impinging propeller slipstream and a uniform jet, it is found that they are remarkably similar. In fact, for equal ground separation distances and initial dynamic pressures, it is found that the data for the radial ground flow in the two jets agree within a few per cent. Since one would intuitively expect the entrainment process to be intimately associated with this radial ground flow, one would conclude then that the two jets would cause similar ground erosion. This conclusion is substantiated by Kuhn's experimental results which show that these two jet configurations produce essentially equivalent ground erosion for a given ground separation distance and average jet dynamic pressure. This demonstrates that flow unsteadiness in the jet and the initial distribution of velocities in the jet do not, by themselves, determine that ground erosion and particle entrainment will occur. Since our aim is to examine those aerodynamic effects that predominate in the entrainment process, these secondary effects can be neglected.

Accordingly the remainder of the discussion will be devoted to four items. First consideration will be given to the effects of viscous mixing in a jet in order to reduce the problem to one of an impinging inviscid jet. Next the available theory for an impinging inviscid jet will be discussed followed by an examination of the available theories dealing with ground boundary layer development under an impinging jet. Finally we will consider the aerodynamic forces on ground particles immersed in the ground boundary layer.

With regard to the viscous mixing of a jet, there is an extensive body of theoretical and experimental data dealing with a free jet exhausting into still air, but only limited experimental data for the viscous decay of an impinging jet. Consequently it is desirable to consider the latter problem by attempting to equate it to viscous decay in a free jet. Typical theoretical and experimental data for the maximum dynamic pressure in a free uniform jet are shown in Figure 2 as a function of ground separation distance. For the free jet, the ground separation distance is taken as the equivalent axial location in the jet. The data in Figure 2 show that the free jet theory and experiment are in good agreement for all axial stations beyond four nozzle diameters from the jet nozzle, but the theory markedly underestimates the effects of viscous decay close to the nozzle. A more accurate theory would be desirable but is not considered necessary in view of the large body of experimental data dealing with a variety of jet flows. For the present purposes one can depend on these experimental data to predict the viscous decay of a free jet.

The data in Figure 2 for an impinging nonuniform jet produced by a ducted fan are seen to agree surprisingly well with the experimental data for a free jet. In contrast, the data for an impinging uniform jet do not agree as well. It appears the lack of correlation between the free jet and impinging jet data is associated with the correlation length. The

decay is compared using the ground separation distance as the axial coordinate in the free jet. However, in the case of the impinging jet the maximum dynamic pressure does not occur near the ground stagnation point but in the order of one or two nozzle diameters away from the stagnation point. The data in Figure 2 show that this is of the same order as the discrepancy between the free jet and impinging jet data. Hence the conclusion is that the problem of viscous decay in an impinging jet is adequately understood on the basis of free jet data, and some further work is required to define a more accurate correlation length.

With the viscous decay problem resolved, one can reduce the impinging jet problem to an inviscid problem by replacing the actual jet with an equivalent inviscid jet. The equivalent jet would have a slightly larger diameter and a reduced average dynamic pressure reflecting the effects of viscous mixing. The problem of an inviscid jet impinging on a ground plane is classical, and theoretical treatments are usually based on the model sketched in Figure 2. In this approach a uniform jet is replaced by a cylindrical vortex tube, and the ground plane is simulated with an equivalent image system. Nonuniform velocity distributions within the jet can, of course, be treated by using a model and image system comprised of concentric cylindrical vortex sheets.

This representation of an impinging jet has been applied extensively in problems concerned with the performance of a helicopter in ground effect, and is generally adequate for that problem since only the flow field at the rotor is required. The present problem is concerned with the flow field along the ground plane, and one might anticipate this model would be inadequate since it misrepresents the jet boundary near the ground plane. That is, the jet boundary should be flared at the ground, and should never intercept the ground plane.

One effect of the flared jet boundary is to distort the flow along the ground so that the maximum velocity along the ground is observed substantially away from the jet. In comparing experimental data with theoretical results obtained with the model in Figure 2, the effects of flaring can be crudely accounted for by normalizing the radial ground coordinate with the radial station at which the maximum velocity occurs. In addition, the effects of viscous mixing must be included. In keeping with the preceding discussion and drawing on other data, this can be accomplished by normalizing the dynamic pressure with respect to the maximum dynamic pressure observed in the ground flow. Typical experimental data have been so normalized and are shown in Figure 3 compared with the theoretical data from the elementary model. Now in the region of the ground stagnation point it can be seen that the agreement is fairly good. However, as one proceeds further out towards the edge of the jet, the disagreement becomes larger, and finally at $R/R_{q_{max}} = 1.0$, the theory predicts infinite velocities. Outside the jet boundary the theory is in substantial disagreement, and at about two jet radii, it underestimates the dynamic pressure by an order of magnitude. Now this discrepancy is due to the fact that the effects of boundary flaring have not been adequately represented. If they were included, we might anticipate much better agreement.

It is noteworthy, however, that the theory does predict the increase in dynamic pressure with increasing ground separation and distance, as indicated by the increment in dynamic pressure between two and four radiis above the ground. This indicates that our method of including viscous effects is quite adequate. The conclusion is that the classical theoretical representation of a jet impinging on a ground plane yields reasonably accurate predictions of the ground flow in the immediate vicinity of the stagnation point. However, the theory is grossly inadequate for predicting the ground flow field in other regions because the model does not duplicate the physical situation with sufficient accuracy.

Returning now to the effects of viscosity in the flow field of an impinging jet, these effects will be important at the ground plane where a boundary layer is formed. The characteristics of this portion of the flow field are of fundamental importance in the particle entrainment problem since the particles which are entrained are initially immersed in the ground boundary layer. Consequently the boundary layer characteristics must contain the conditions for entrainment.

Evidently there are only two boundary layer solutions which have bearing on the present problem. The first is the classical solution for an axisymmetric stagnation flow of infinite width. In applying this theory to the problem of an impinging jet, it is found that the theory is valid only in the immediate vicinity of the stagnation point. The second theory having bearing on our problem is a recent solution by M. B. Glauert for a radial wall jet. He considered a source-type flow along a wall and obtained a solution for the case when the pressure along the wall is constant. Consequently this theory is applicable to the jet impingement problem only at ground positions substantially away from the jet boundary.

The available three-dimensional boundary layer theories can be applied in the present problem only in the immediate vicinity of the stagnation point and substantially outside the jet. In contrast, our interests are with the entire boundary layer from the stagnation point to several jet diameters from this point. There are no theoretical or experimental data covering this range, and it appears the only recourse is to rely on two-dimensional theory which includes the effects of pressure gradient. In applying this theory, one would have to include the important three-dimensional effects that influence the boundary layer growth.

In considering the aerodynamic forces on particles immersed in the boundary layer, it is recognized that the effect of the wall is to result in a lift force. In addition, the nonuniform velocity distribution in the stream acting on the particle will produce a lift force. There are no theoretical or experimental data dealing specifically with this problem; however, an estimate of the particle forces can be obtained by representing the ground particle as a sphere, and assuming the wall effect and the effect due to the velocity gradient can be superimposed. As indicated in

the sketch at the top of Figure 4, this has been done by assuming the dominating velocity gradient is that intercepting the sphere center. The lift on the particle has been estimated by adding the wall or potential lift and velocity gradient or shear lift. The drag was takentto be that for uniform flow, and the static friction was taken to be the force necessary to move the particle out of the valley formed by two equal diameter spheres. These forces were used to determine the critical particle sizes for entrainment in a laminar boundary layer plotted in Figure 4. Particles on the right of the lift or drag line are neither lifted nor rolled by the stream, while for particles to the left of either the lift or drag line, the respective force is greater than the weight or static friction and will be entrained.

To illustrate the conditions necessary for entrainment, consider a laminar boundary layer thickness of a half inch, a free-stream velocity of 60 fps, and a particle density of 120 psf. The corresponding value of the abscissa is $\frac{\rho_s g \delta}{\rho/2\, V_0^2} \approx 1/2$. Figure 4 shows that the finest dust ($r <$ .005") will be rolled because of aerodynamic drag. All particles with a radius .005" $< r <$ .01" will not be entrained. Particles with a radius of 0.1" $< r <$ 0.3" will be entrained by both the lift and drag mechanism, and larger particles will be rolled by the drag mechanism.

A qualitative understanding of where entrainment occurs under a jet can be obtained by considering a uniform jet impinging on the ground plane. Now, at the center of the jet there is a stagnation point and a finite boundary layer thickness. This corresponds to an infinitely large value of the abscissa, and there would be no particles entrained near the stagnation point. Proceeding radially outward from the stagnation point, the velocity increases faster than the boundary layer thickness, corresponding to decreasing values of the abscissa in Figure 4. At some point a critical radial station will be reached at which the loading parameter, $\frac{\rho_s g \delta}{\rho/2\, V_0^2}$, will equal one. At this station particles will begin to roll. Proceeding radially outward beyond this station, a second critical station will be reached at which $\frac{\rho_s g \delta}{\rho/2\, V_0^2} \approx 0.7$, and at this particles equal in diameter to the boundary layer thickness will be lifted directly into the stream. Proceeding still further outward from the stagnation point, both larger and smaller particles will be entrained until a radial station is reached where the velocity reaches a maximum. As one proceeds still further outward, the free-stream velocity will decrease and the loading parameter will increase until it exceeds the value for which entrainment is possible. It can then be seen that entrainment can occur only in an annular region under an impinging jet, regardless of the ground composition. The extent of this annular region is fixed by both the disk loading of the jet and by its size, through the boundary layer thickness.

With this qualitative understanding of the entrainment process, we can reach several important conclusions. First it should be emphasized that there is a strong scale effect in that entrainment depends on the relative size of the ground particle in comparison with the boundary layer thickness. The latter in turn depends on the jet velocity and the size of

the jet. Consequently the results obtained from small-scale erosion experiments must be evaluated with considerable caution since this scaling law is as yet undefined.

Secondly, it is noted that there are two mechanisms to entrain particles. As previously suggested, the particles can be rolled along the ground plane and through a series of elastic impacts with other particles, be bounced into the main stream. It is difficult to speculate on this mechanism owing to its random nature. The other mechanism is that the particles can be lifted directly into the main stream.

The third important conclusion is that entrainment might be controlled by altering the ground boundary layer. The particle lift and drag are respectively determined by the product of the velocity and velocity gradient, and by the square of the velocity acting on it in the boundary layer. The magnitude of these forces can be diminished by diminishing these quantities, that is, by promoting boundary layer separation. In keeping with the observation that entrainment can occur only in an annular region, it would be necessary to maintain a separated flow only in an annular region of finite extent. This approach to the problem should be given detailed consideration.

In summary, it would be desirable to be able to quantitatively predict the regions under an impinging jet where particle entrainment would occur. This is not feasible because the data for particle forces in nonuniform flows is inadequate. Assuming these data were available we would then require data on the boundary layer characteristics under the jet. Both the theory and experimental data on three-dimensional boundary layer development, including pressure gradient effects, are presently inadequate. If these developments were available, we would then require the distribution of ground pressures under the jet, which could be obtained from the theory for an inviscid jet. The existing inviscid theories are also inadequate. Consequently, further research is required in each of these areas before we can predict and understand the entrainment process. With this quantitative understanding in hand, consideration can then be given to alleviating the problem.

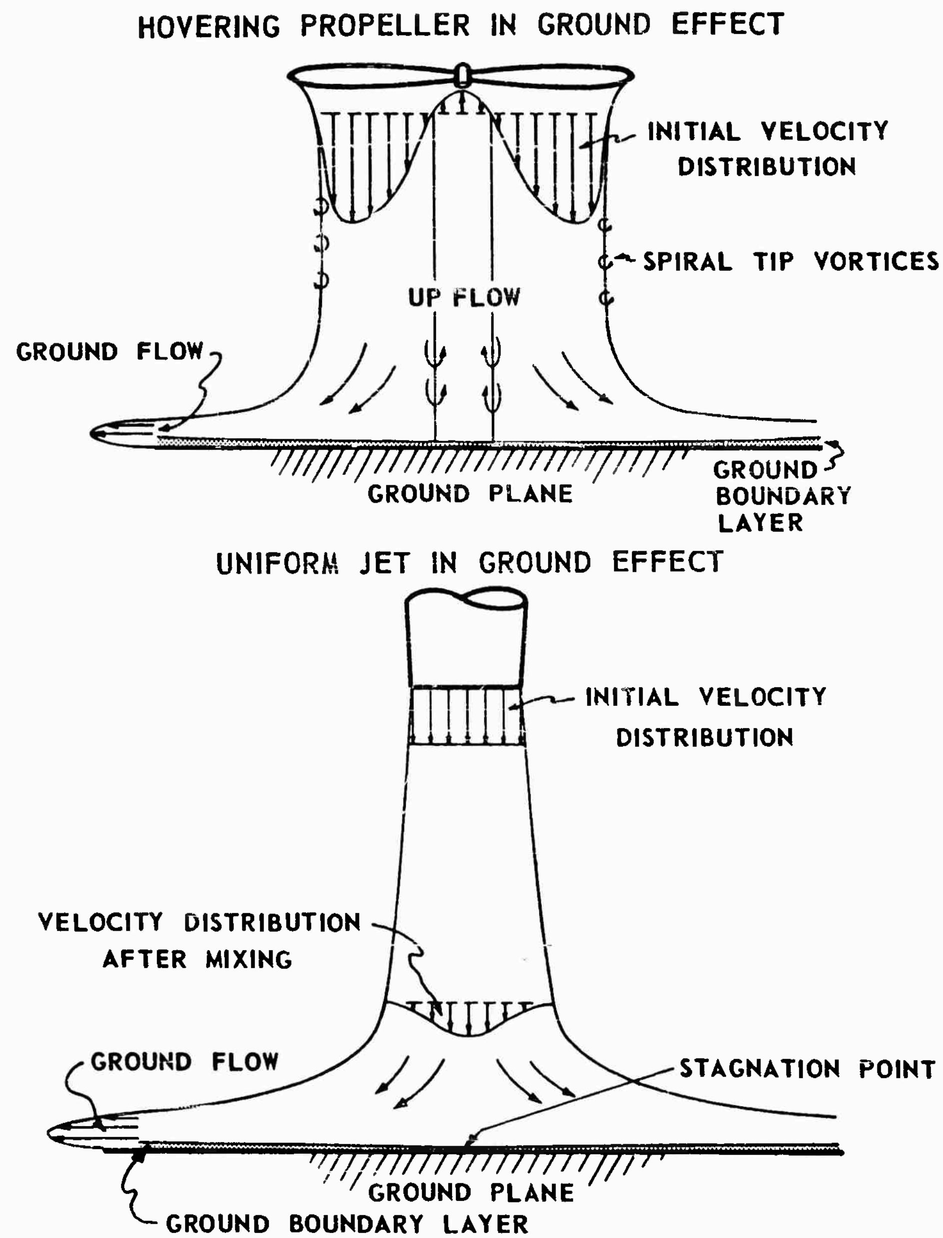

Figure 1. TYPICAL SLIPSTREAMS IMPINGING ON THE GROUND.

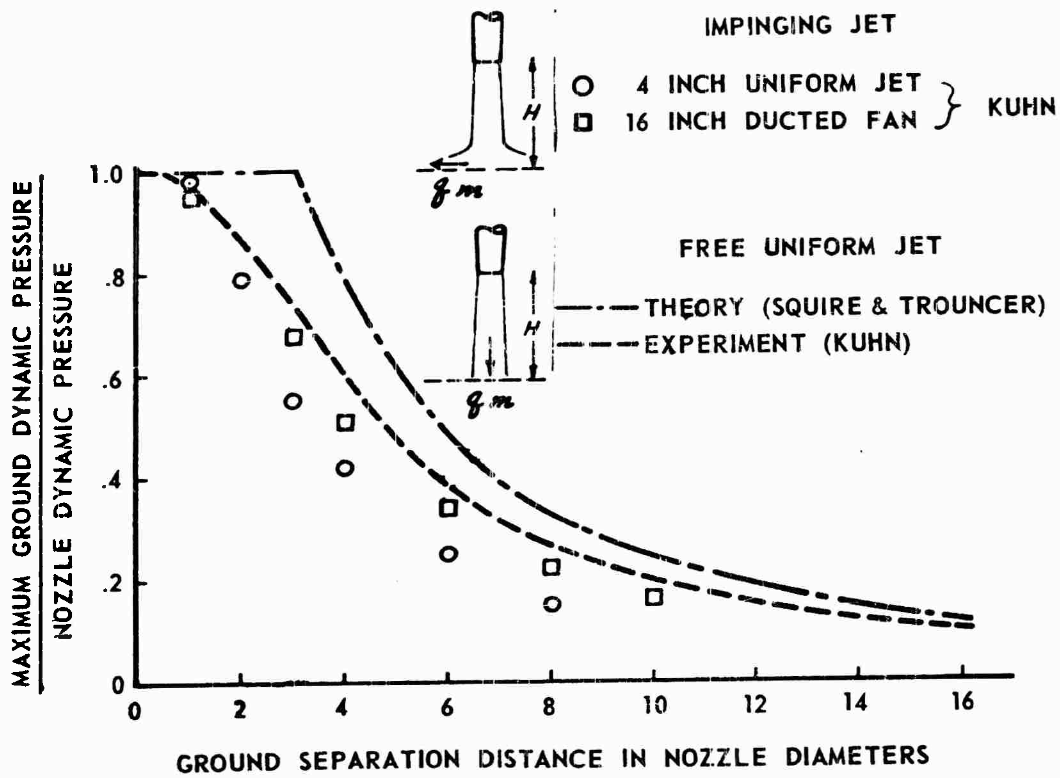

Figure 2. VISCOUS DECAY OF AN IMPINGING JET.

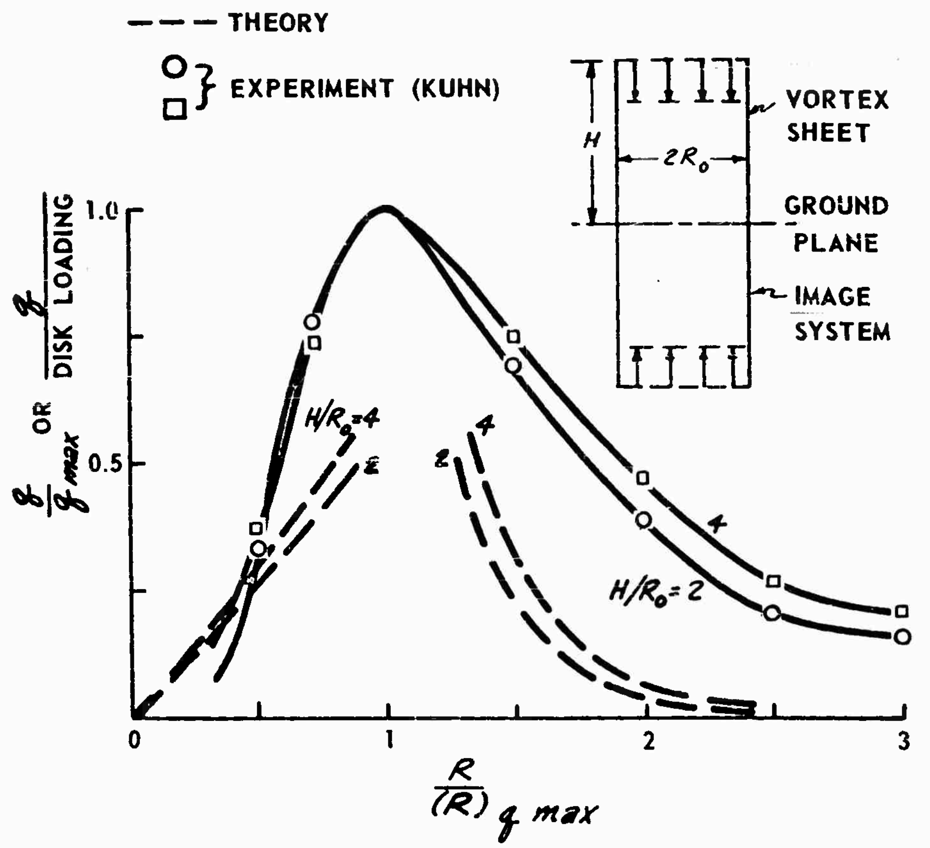

Figure 3. COMPARISON OF THEORETICAL AND EXPERIMENTAL GROUND FLOW UNDER AN IMPINGING UNIFORM JET.

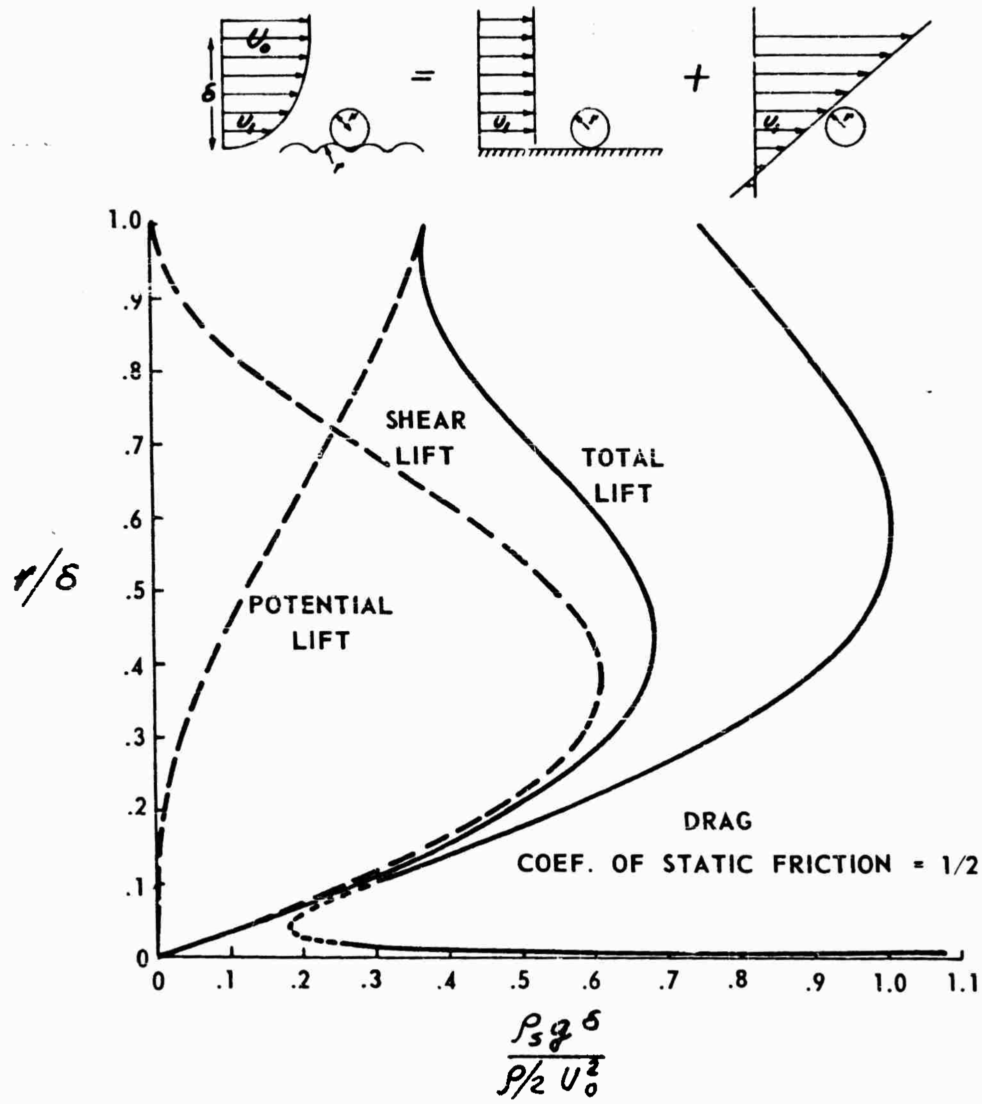

Figure 4. CRITICAL PARTICAL SIZES FOR ENTRAINMENT IN A LAMINAR BOUNDARY LAYER.

PAPER NO. 11

MODEL AND FULL-SCALE TEST OF GROUND IMPINGEMENT OF A JET VTOL

by

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GROUND IMPINGEMENT OF A JET VTOL AIRCRAFT

The general problems imposed by various types of ground environment on VTOL aircraft operation may be divided into two categories as in Figure 1. The pilot is concerned primarily with the safe

Problem Areas	
Aircraft	Ground Installation
Vision	Surface Erosion
Recirculation	Foilage Damage
Skin Damage	Personnel
Detection	Ground Equipment
	Signature

Figure 1

operation of the aircraft. Experiences with helicopters have shown that dust and snow clouds produced by the exhaust obscur vision sufficiently as to reduce safety to unacceptable levels.

Recirculation of gases and debris by the engines may produce high inlet temperatures resulting in thrust loss while foreign objects could produce engine damage perhaps even failure. Structural damage may also occur by impingement of rocks, sand or hot gases.

One of the most serious problems in tactical operations may be the creation of dust clouds that are easily detected by the enemy. This must be reduced if enemy counter measures are to be avoided.

Site selection should permit location adjacent to the supported unit without increasing the hazards to the unit. Ground personnel must not be subjected to excessive dust or debris. It is desirable to permit location of ground equipment near to the landing site without permitting damage to it.

For repeated landings and take-off, the surface erosion and foilage damage may increase the dust and debris problem as well as increasing the signature inviting enemy counter action.

The independent variables with which the designer may work are listed in Figure 2.

Independent Variables
(1) Downwash velocity
(2) Temperature
(3) Configuration

Dependent Variables
(1) Size of landing site
(2) Landing site preparation

Downwash velocity is of interest in dust production as well as in the erosion of soil directly beneath the vehicle. Tests by Kuhn of NASA have shown erosion of dry, non-compacted sand at dynamic pressures of 1 to 3 psf. These disk loadings are obviously too low for helicopters and VTOL aircraft. Compaction will permit higher velocities. Transport velocities recommended for conveying materials are based on the sum of the floating and material velocities and may be approximated by the following equation:

$$V = 1030 \sqrt[3]{W} \quad (d) \quad + \quad 582.5 \sqrt{W}$$

v = velocity in fpm

W = bulk density of material lb/ft^3

d = particle equivalent diameter inches

Figure 3 shows this relation for an average bulk density of 100 pounds per cubic foot for clay, gravel, and sand. The transport velocities approximate those required for moving airborne particles. Rolling will occur at lower velocities.

If the particles are compacted as in soil, the dynamic pressures required for movement may approach the transport velocities. Tests with water have shown erosion to begin at dynamic pressures as high as four times that of the floating velocity.

Exhuast temperatures ranging from ambient up to 1200°F may be expected of VTOL aircraft. The higher temperatures defoliate grasses and brush presenting a fire hazard as well as signature problems. The intermediate range up to 350" expected with lift fans or ejector aircraft do not appear to offer problems with temperatures.

Configuration of the exhaust outlets appears to be the major area in which design ingenuity may permit reduction of the problem. A single circular outlet has been studied and tested by NASA. Recent tests show that dynamic pressures outside the plane of the rotor do not depend on disk loading but rather only on gross weight. Further, the overturning moments are actually lessened at the higher disk loading. Figure 4 shows planform effects of configuration on the flow. On the left side of the figure is a circular outflow. Dust and larger particles will be moved radially. This will present a problem of vision for vehicles during landing or take-off. The central figure shows two parallel outlets as for several fuselage mounted lift engines or ejectors. Here the outflow is principally normal to the flight path so that vision fore and aft is improved at the expense of side vision. A tilt wing design as shown on the right appears to aggravate the forward vision problem. A test rig which has two parallel

outlets is shown in Figure 5. The equivalent disk loading of this machine is approximately 115 psf out of ground effect. The outflow is principally normal to the long axis. Figure 6 shows the flow patterns, experienced with this machine. At a height of two feet, the maximum outlet temperature of the gases was 275° directly below the rig. The high velocities fan outward from the sides while fore and aft the velocities are much lower although the temperature of the gases are approximately the same as in the side flow. In the sections 45 degrees from the long axis, the flow is inward toward the side and fore and aft flow. Build-up of the boundary layer prevents movement of sand in these areas at short distances from the machine. Reingestion of hot gases by the engines has occurred in quartering winds although it was not generally severe. Smoke and flow tests have defined an area above the side flow where temperatures are ambient. In fact, reduction of the local temperatures have occurred due to entrainment of air some distance from the ground.

Recent tests of static pressures on a solid ground plane have resulted in the observance of a negative pressure just beyond the periphery of the jet. Figure 7 shows a plot of data from one model near the ground. This data was obtained with an outlet 5.8" by 16 inches. At a distance of 14 inches the static pressure is negative and remains so for approximately 5 inches.

Figure 8 is a contour plot of the static pressure distribution for a rectangular outlet with an aspect ratio of 3. The negative pressure areas mentioned previously may be noted. The significant effect of the configuration also may be recognized. Speculation is that this negative pressure creates the cratering observed in other tests as it is located at the same distance from the center of the jet. Once the crater is established, saltation may increase the disturbance. If this area is protected by a membrane, such as the Army ground cover, it appears possible that erosion and perhaps dust production will be significantly reduced. Contouring of the membrane by trenches or banks may further help.

In summary, it appears that in addition to equivalent disk loading and temperature effects, one must consider the outlet configuration in assessing ground impingement effects. It is felt that use of a light weight membrane will permit repeated landings without leaving as large a signature as the tracks of current aircraft on the soil.

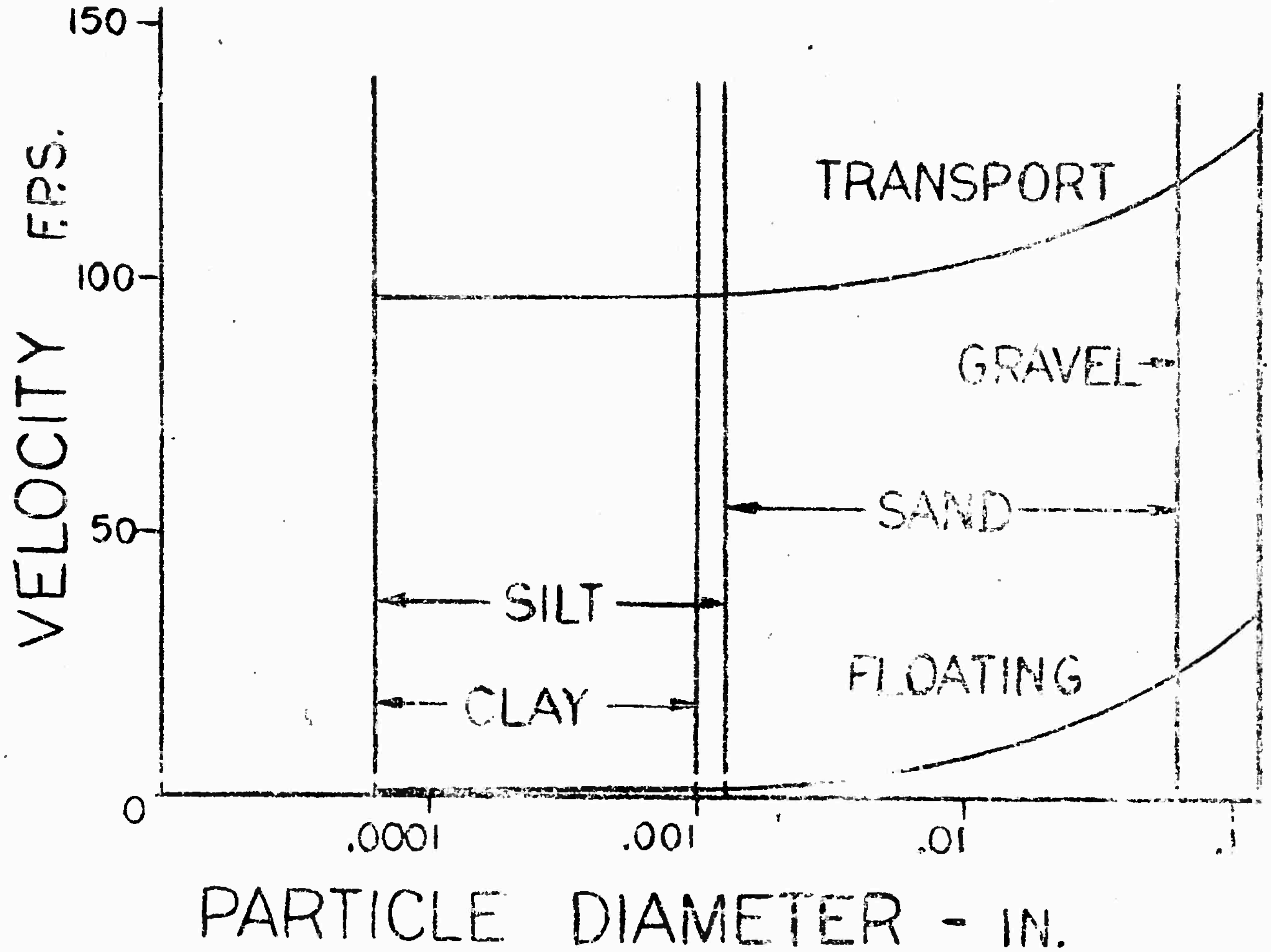

150
100
50
0
VELOCITY F.P.S.
TRANSPORT
GRAVEL
SAND
SILT
CLAY
FLOATING
.0001
.001
.01
.1
PARTICLE DIAMETER - IN.

FIG 3

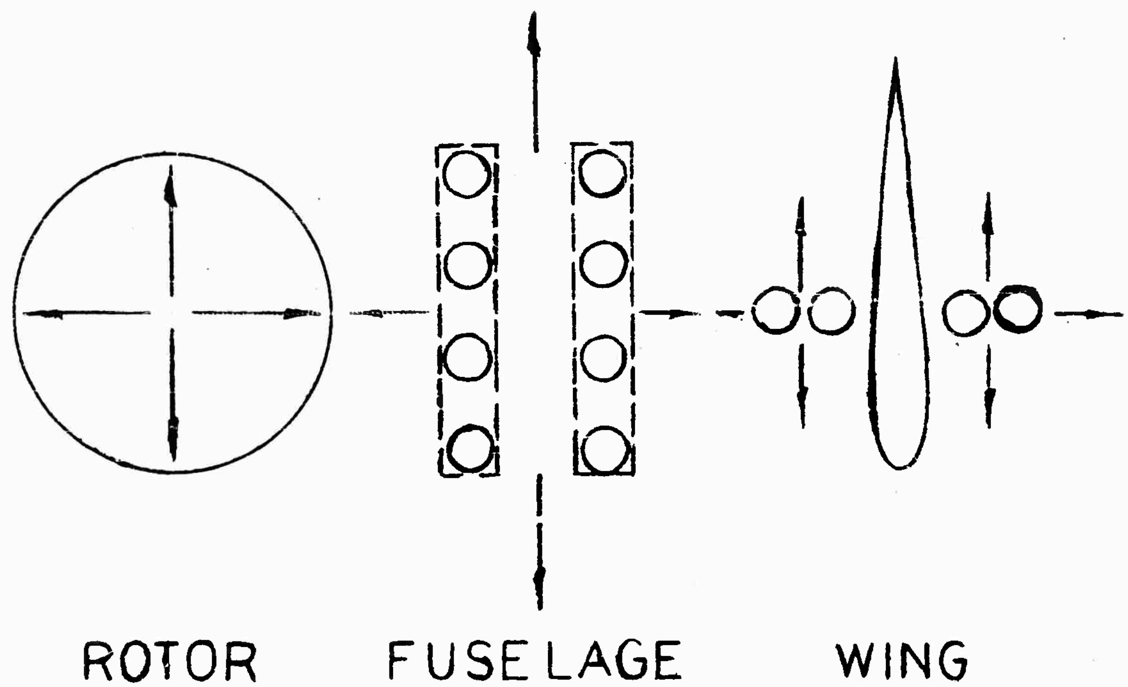


FIG. 4

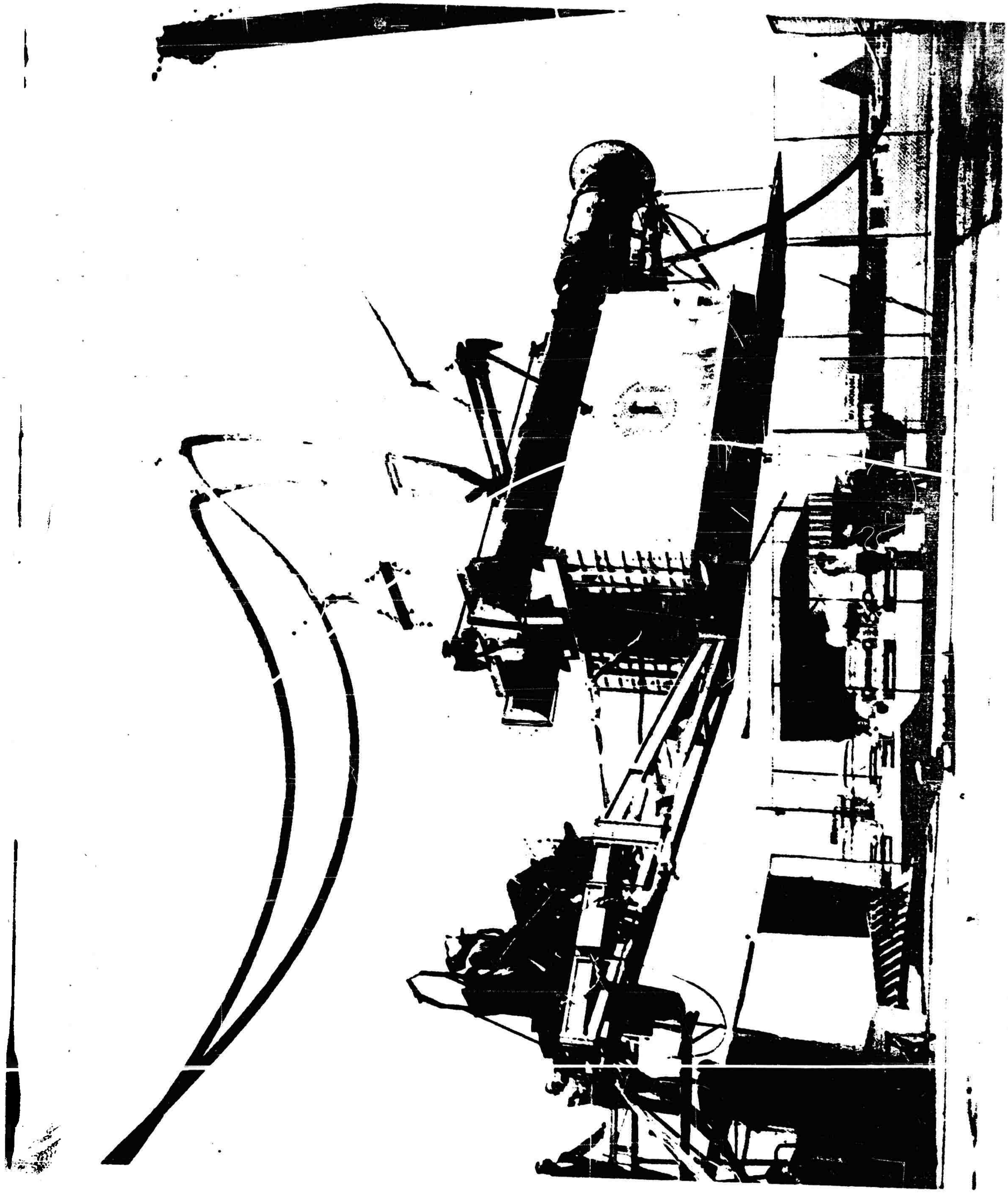


Figure 5. Test Rig Utilizing Two Parallel Outlets.

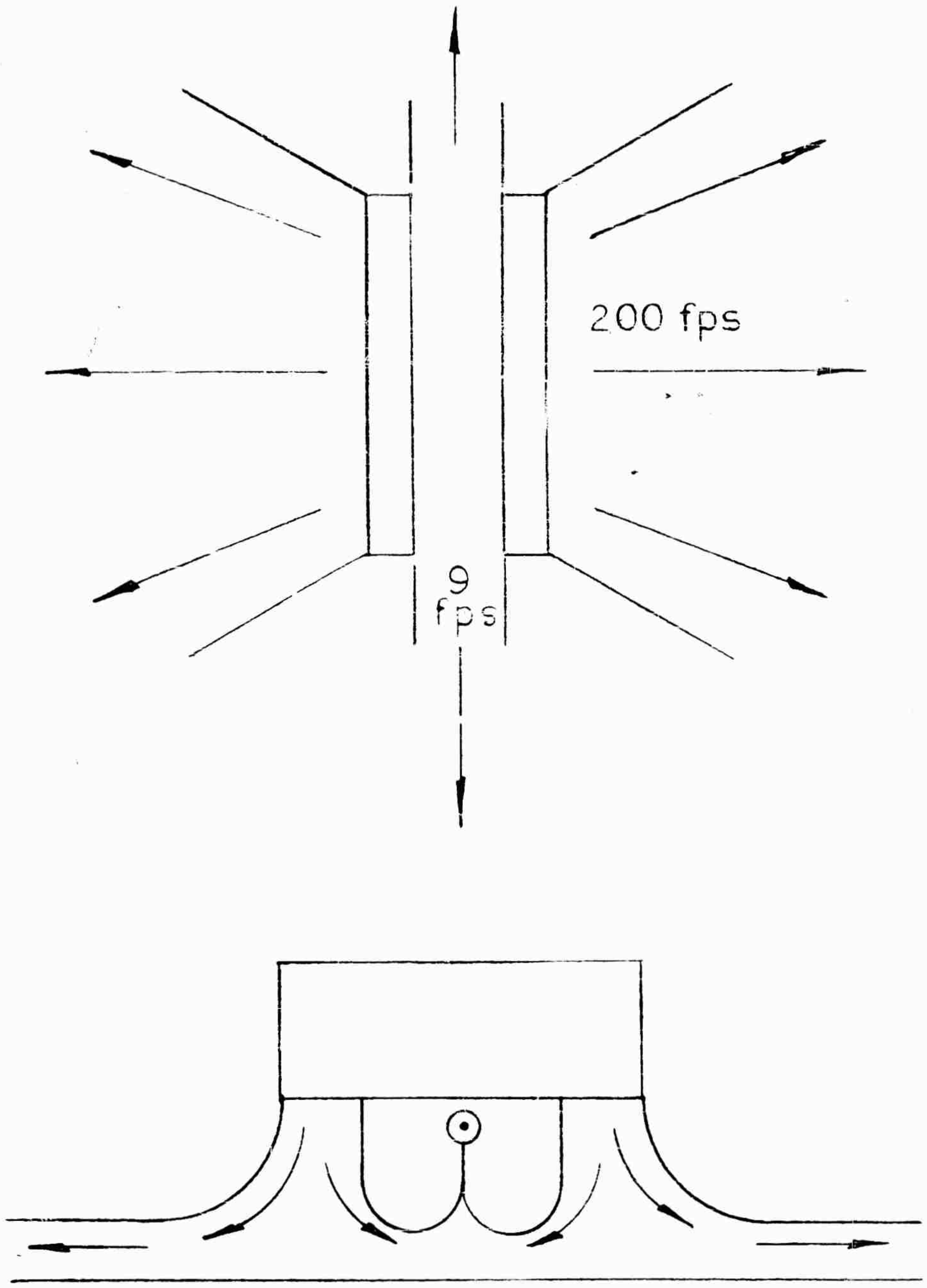


FIG 6

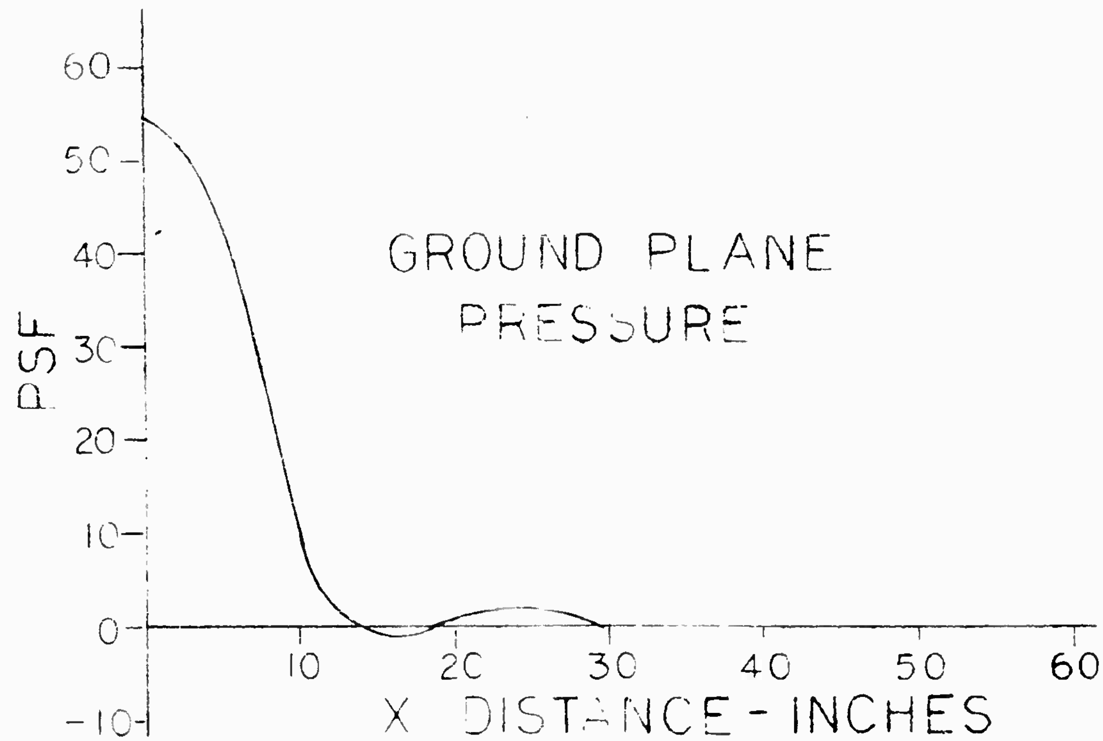
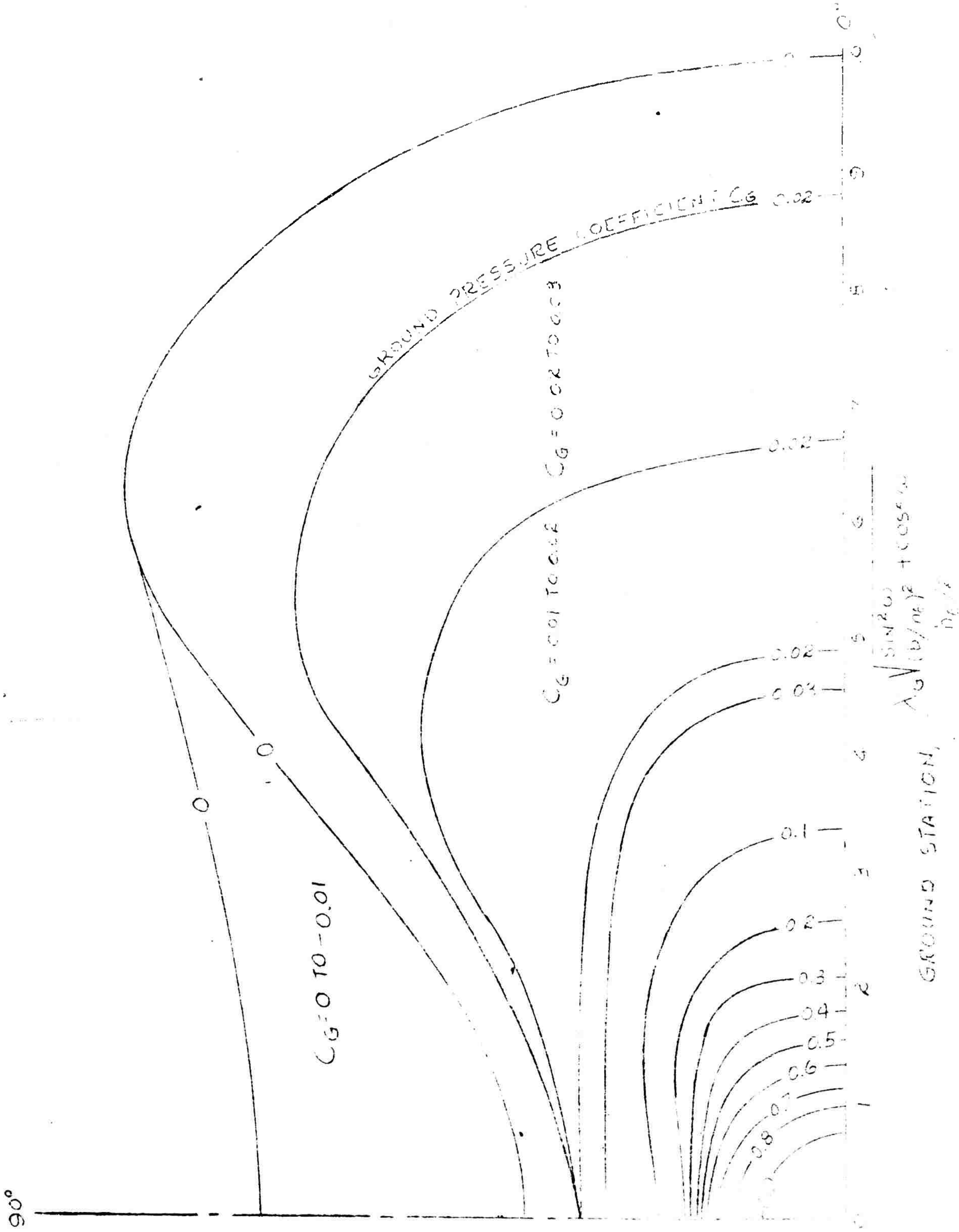

GROUND PLANE
PRESSURE
PSF
60
50
40
30
20
10
0
-10
10
20
30
40
50
60
X DISTANCE-INCHES

FIG. 7



GROUND PRESSURE COEFFICIENT, C_G
C_G = 0 TO -0.01
0
0
0.02
0.03
0.1
0.2
0.3
0.4
0.5
0.6
0.8
90°
0°
GROUND STATION,

FIG. 8

PAPER NO. 12

DOWNWASH: SOME EXPERIMENTAL RESULTS AND OPERATIONAL EXPERIENCES

by

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DOWNWASH IMPINGEMENT - SOME EXPERIMENTAL AND OPERATIONAL OBSERVATIONS

Introduction

The effects of the downwash produced by direct lift aircraft on the operational effectiveness of a VTOL has been a matter of concern ever since the beginning of widespread use of helicopters in unprepared areas. Although the operational difficulties caused by the movement of sand, loose soil, cinders, and snow were not insurmountable at the values of disk loadings of 3 to 4 pounds per square foot great concern was expressed by military operators upon introduction of a disk loading of 7.5 lbs/sq. ft. in the Sikorsky H-37 helicopter. The extreme difficulties experienced by flight and ground crew in desert operations of the H-37 were reported by Barrios in Reference (3). It was only through the development of special flight and ground techniques that operations under the desert terrain environment were possible, even though with difficulty. It was this experience which led this writer to state in Reference (4) that the maximum practical disk loading for operation in unprepared areas was of the order of 15 lbs/sq.ft.

The problem of downwash impingement effects becomes much more acute in consideration of the more recent VTOL designs for which disk loadings greatly exceed fifteen pounds per square foot. The satisfactory application of such vehicles to military operations requires careful consideration of the nature of the terrain to be encountered, the degree to which preparation of the landing area is possible, overall effects of the downwash field, and the mission requirement particularly with regard to versatility of VTOL operation. It is the authors intention here to review briefly the present status of the knowledge with regard to the downwash effects and to point out some specific experiences encountered in helicopter operations.

The Downwash Flow Field

The first broad investigation of the nature of the flow under a rotor or propeller was that performed by Sikorsky Aircraft and reported by Fradenburgh in Reference (1). This investigation presented smoke flow photographs of the rotor under various operating conditions typical of which is that for a hovering rotor 0.5R above the ground shown in Figure 1. The most significant features shown in the photograph are the low velocity region at the center of the rotor for operation in ground proximity, the annulus of high velocity flow impinging on the ground, and the strong annular vortex flow apparently producing a scrubbing action on the ground. For greater heights above the ground the high velocity annulus shrinks to a diameter of $\sqrt{2}/2$ times the rotor diameter; however, the velocities at the ground persist to considerable heights above the ground.

The effect of rotor height above the ground on the profiles of velocity normal to the ground is shown in Figure 2 for various distances from the rotor axis. These results have been substantiated by the tests reported in References 5 and 6. The persistence of the ground velocity for large values of rotor or propeller height above the ground is apparent. Decay in the radial velocity with distance from the rotor axis is also apparent. The downwash decay data presented by N.A.S.A. recently in Reference (2) substantiate the data of Figure 2. On the basis of these data it may be concluded that:

1. The erosion of soil or movements of particles will be most intense where the shed vortices contact the ground.

2. A relatively undisturbed region exists at the center of the rotor which is significant for any operations requiring the presence of personnel or objects under the aircraft.

3. The disturbance dynamic pressure is directly proportional to the disk loading.

4. As shown in Reference (2) at large distances from the rotor axis, the downwash dynamic pressure for a high disk loading will be of the same order of magnitude as that for a considerably lower value of disk loading due to the velocity decay with distance from the axis of rotation.

Flight and Ground Crew Problems

An interesting operational photo of the disturbance produced by downwash in operation over a beach is shown in Figure 3. The ground crew are wearing eye protection equipment but are apparently experiencing difficulties due to the sand and the downwash velocity. The undisturbed region under the rotor is apparent. Figure 4 shows the same operation with the helicopter somewhat closer to the ground. The amount of sand being moved in these photo(s) is extremely little compared to that reported by Barrios in Reference (3). In this report, the sand cloud was so dense as to conceal from view all objects beyond the helicopter rotor. This loss of visibility was hazardous to ground crew and made spotting of aircraft and/or cargo inaccurate. It was found necessary to develop a ground lighting system in order to complete the mission.

At the velocities produced by a disk loading of 7 to 8 lbs/sq. ft. it is difficult to walk into the flow for the handling of slung cargos.

Aircraft Damage and Maintenance

The damage inflicted on the components of the aircraft in flight over unprepared areas may be so great as to prohibit operation. As an example of the type of damage that can be inflicted upon rotating

components such as rotors and propellers, reference is made to Figure 5. Normal atmospheric dustiness has caused erosion of the rotor blade tip cap to the point where a hole has been produced after approximately 1400 hours of operation. To guard against excessive damage to the blade leading edge, a stainless steel protective strip was bonded to the leading edge. Although the strip successfully prevented leading edge erosion due to water and general atmospheric contamination, Marine operations in coastal areas produced the condition shown in Figure 6. The ridges appearing on the leading edge strip were caused by the cold working of the metal strips under impact from sand particles after approximately 200 hours of operational time. This difficulty has been eliminated by increasing the material thickness.

A problem more difficult to resolve is that of foreign objects ingestion into the engine particularly where turbines are employed. Rapid deterioration of engine performance requiring frequent overhaul can be expected. In recent operations over salt water serious losses in power were experienced due to deposits of salt in the engine inlet passages. A solution to this problem is presently being sought. As a result the question has arisen as to the conditions under which injection occurs. Previous smoke flow studies under zero wind hovering conditions have indicated no tendency for the downwash to recirculate. Studies made of the flow under ambient wind conditions however have shown large recirculation flow on the upwind side of the rotor. Moving pictures of a helicopter hovering over snow show that the amount of recirculated flow encountered by portions of the helicopter is affected by the magnitude of the wind and also by the height of the aircraft above the ground. It appears that a hovering height of approximately one rotor diameter is sufficient to avoid ingestion effects for operation over snow or water. Systematic studies of this problem are required for ranges of disk loading typical of VTOL aircraft and for various terrains.

Concluding Remarks

1. The magnitudes of downwash velocities and dynamic pressures for direct lift systems have been adequately determined for evaluation of general designs.

2. The maximum permissible values of disk loading for operation over various unprepared terrains have been sufficiently well established in Reference (2) to permit design evaluation for specified operational terrain requirements.

3. VTOL operation at values of downwash dynamic pressures greater than approximately 15 lbs/sq.ft. will require preparation of landing areas.

4. Operation over water or unprepared areas requires development of means for protecting engines from foreign object ingestion or salt deposition.

5. Attempts to operate VTOLs with high disk loadings from many types of unprepared area will result in serious operational and maintenance problems.

6. To provide for satisfactory operation of VTOL aircraft over unprepared areas research should be concentrated on the development and evaluation of ground treatment methods, ground covers, and devices designed to suppress the erosion producing flow.

List of Figures

References

1. Fradenburgh, Evan A., "Flow Field Measurements for a Hovering Rotor Near the Ground," presented at A. H. S. Western Forum, September, 1958.

2. N.A.S.A. - - Copies of slides to be presented at N.A.S.A. Conference on V/STOL Aircraft, Langley Research Center, November 17-18, 1960.

3. Barrios, Willie W. J., "Some of the Operational Problems Encountered During Service Testing of the H-37A Helicopter," presented at A.H.S. Western Forum, September, 1958.

4. Michel, P. L., "Research and Design Progress Toward High Performance Rotary Wing Aircraft," Journal of A.H.S., April, 1960.

5. Kuhn, Richard E., "An Investigation to Determine Conditions Under Which Downwash from VTOL Aircraft will Start Surface Erosion from Various Types of Terrain," NASA TN D-56, dated September, 1959.

6. Hiller Aircraft Corporation, "VTOL Downwash Impingement Study, Velocity Survey," U. S. Army TREC TECH. REPT. 60-58, August, 1960.

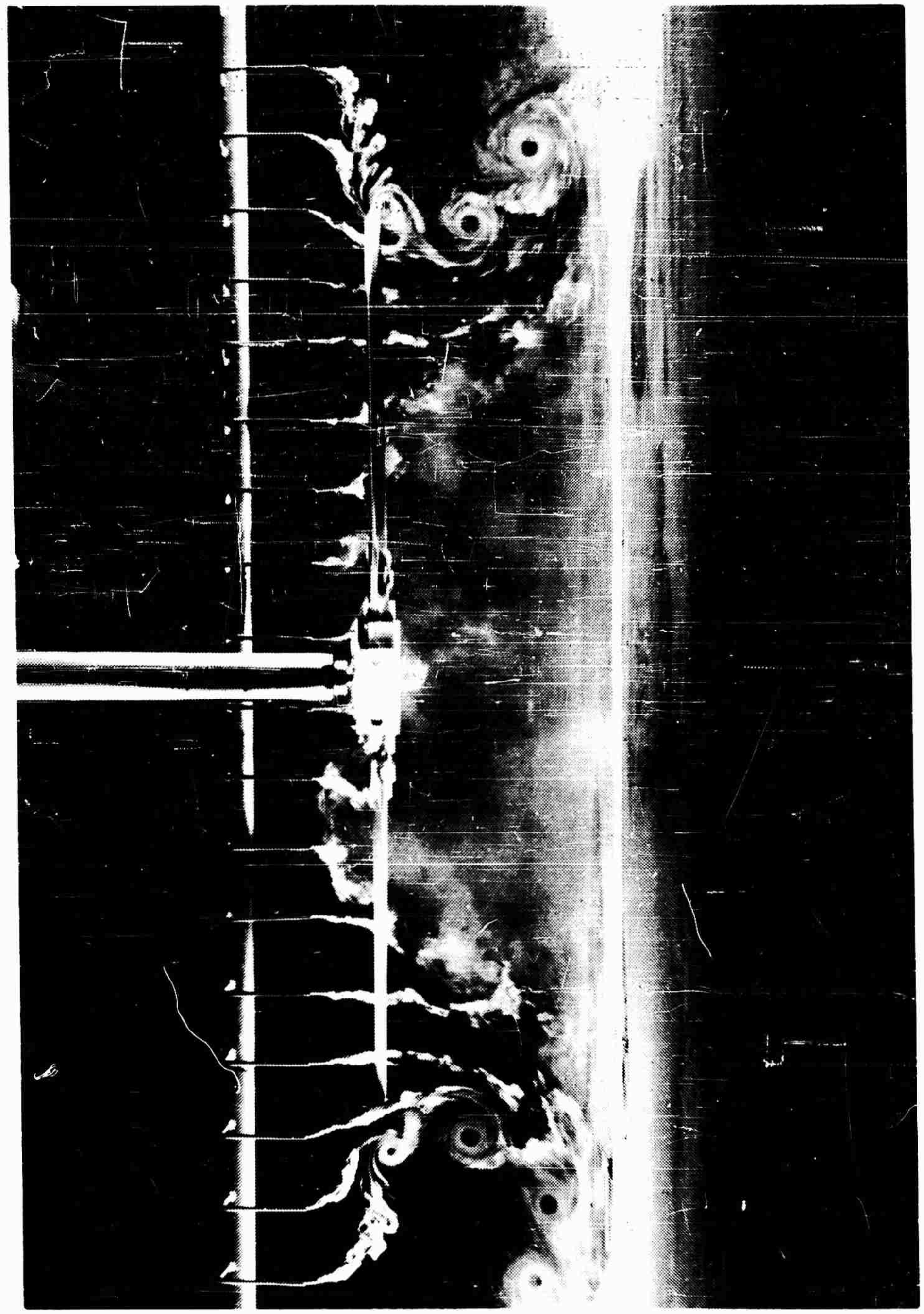

Figure 1. Smoke Flow-Rotor 0.5 Radius Above Ground.

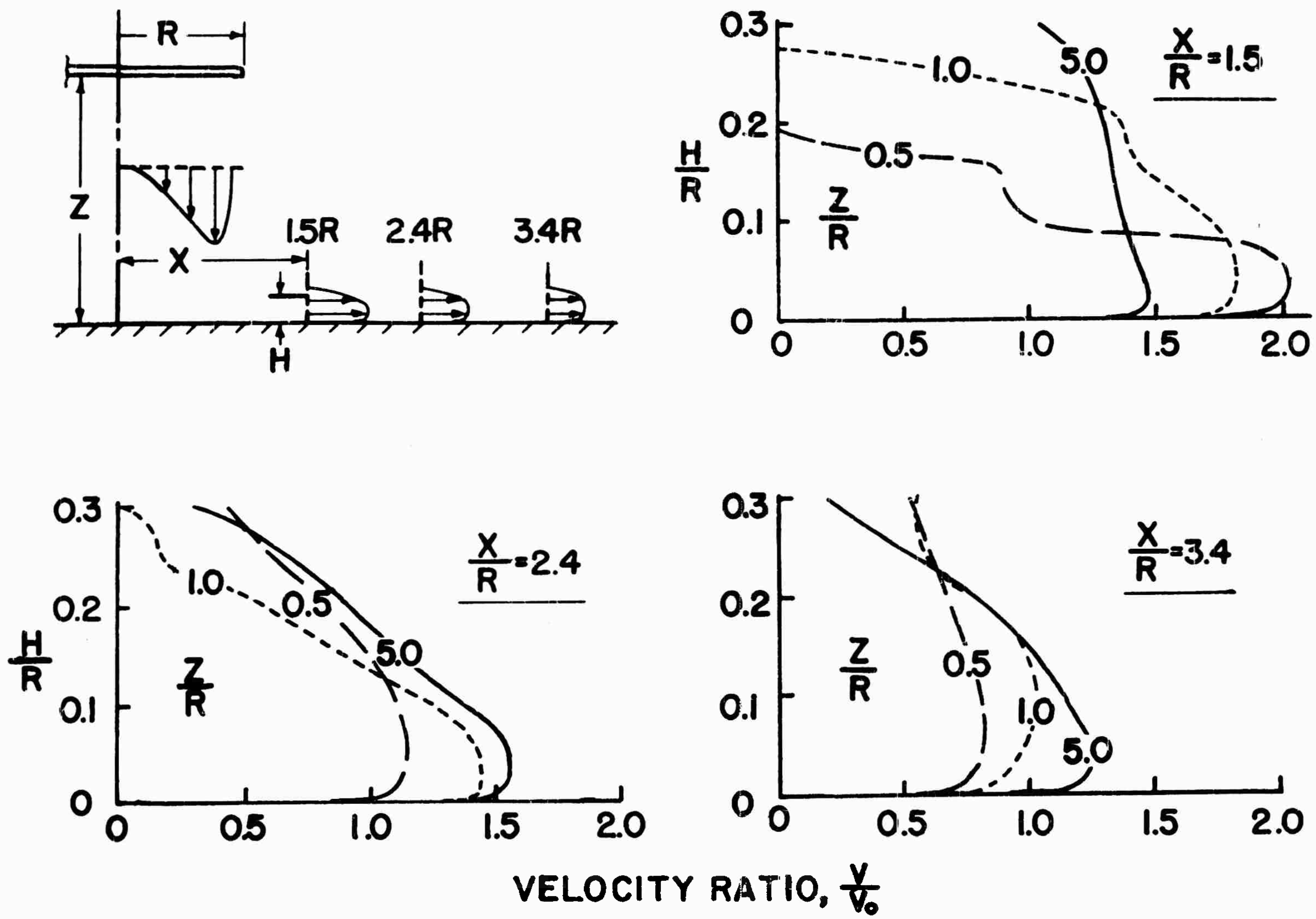

Figure 2. Velocity Profiles Along Ground.

Figure 3. S-60 Crane Helicopter.

Figure 4. S-60 Crane Helicopter.

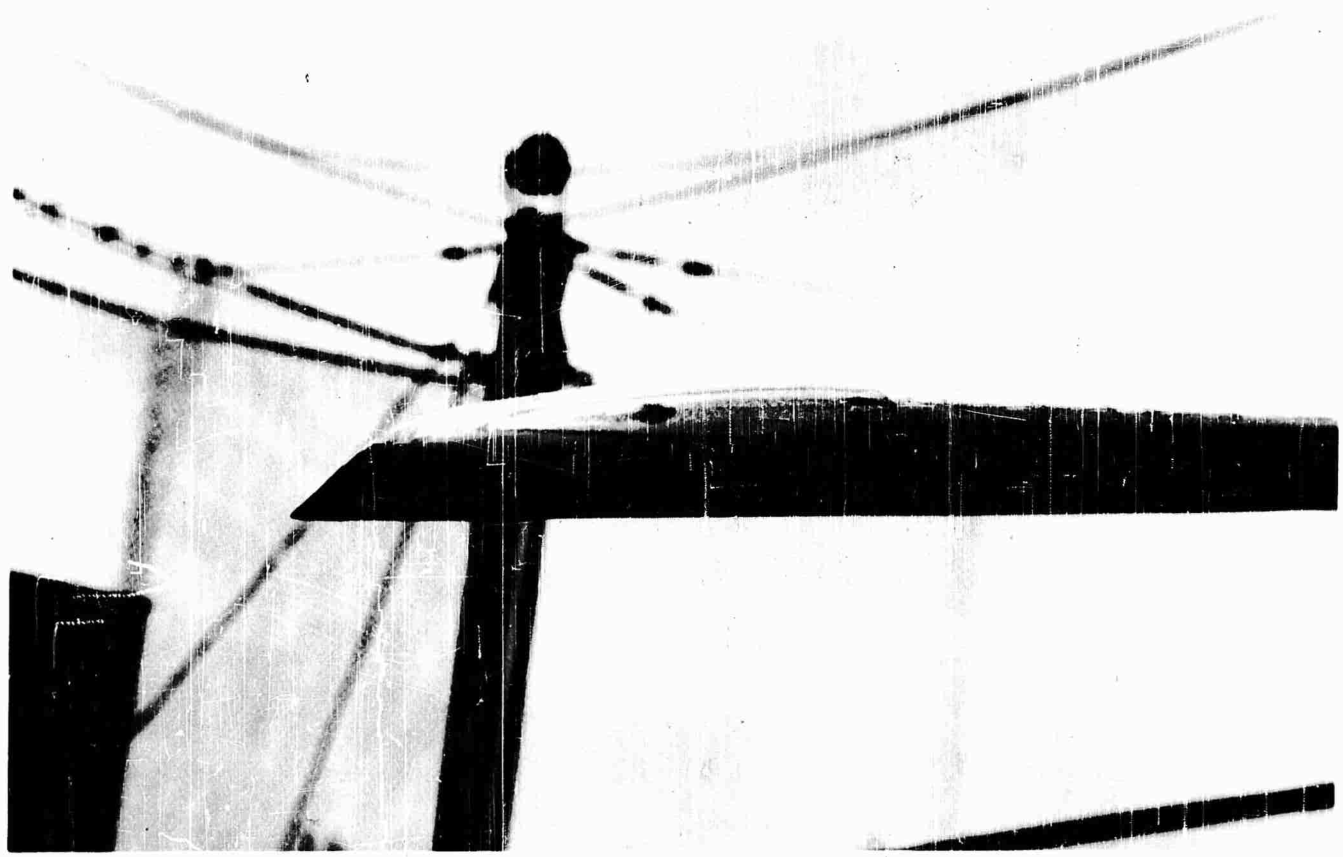

Figure 5. Blade Tip Cap Erosion.

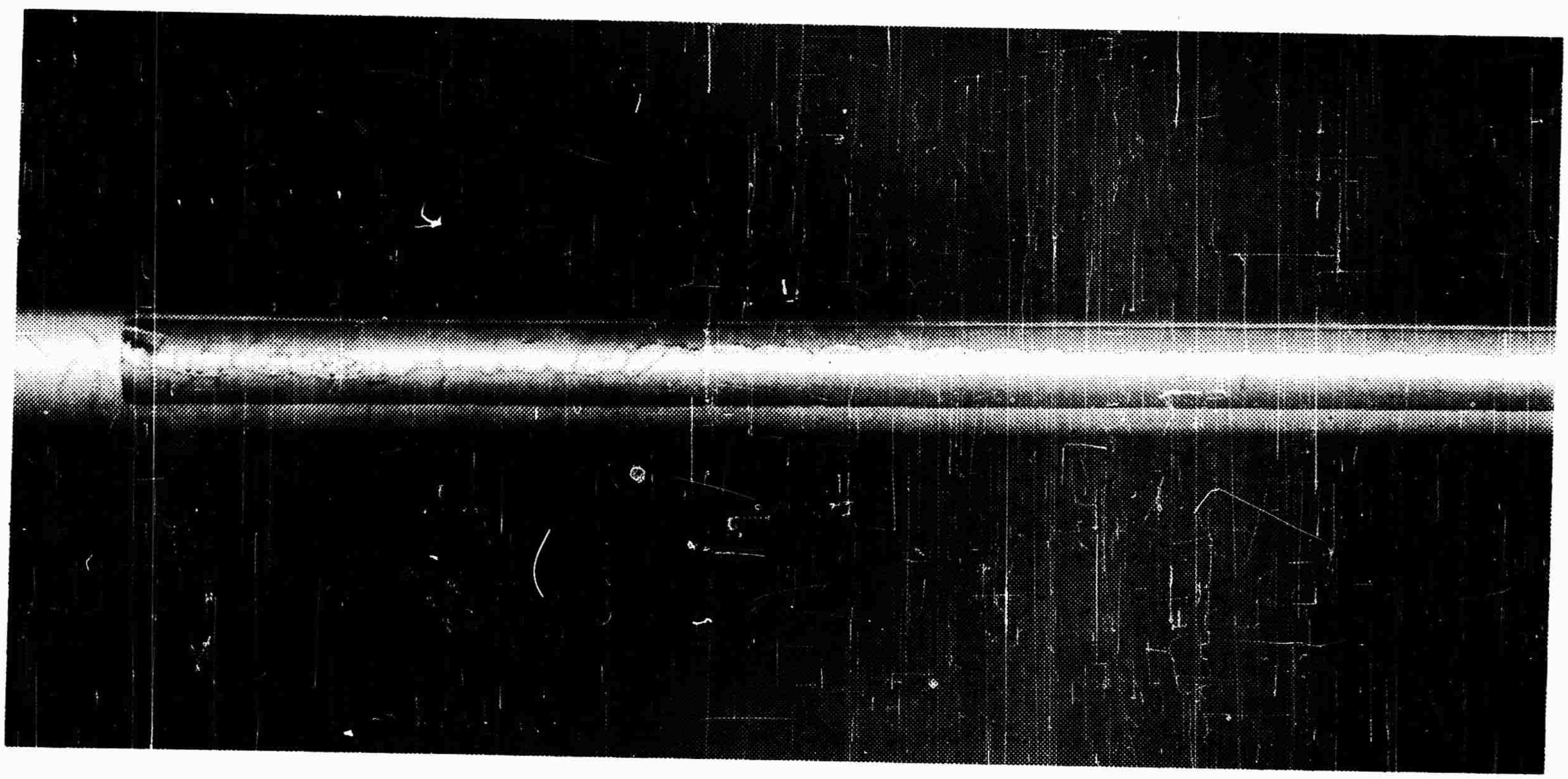

Figure 6. Rotor Blade Deformed Erosion Slip.

PAPER NO. 13

SIMULATED VTOL EXHAUST IMPINGEMENT ON GROUND SURFACES

by

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SIMULATED VTOL EXHAUST IMPINGEMENT ON GROUND SURFACES

By C. A. Grotz
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INTRODUCTION

The effects of VTOL aircraft exhaust impingement on the ground plane is a serious problem which must be considered in the design of a jet-powered VTOL airplane as well as in the development of the operational concepts for the aircraft. The ground blast from the lifting device can result in severe erosion and deterioration of the ground surface and can produce flying debris which may be sucked into the engine inlet of the aircraft causing extensive damage to engine compressor blades.

To obtain a better understanding of the severity of this problem, the Aero-Space Division of the Boeing Airplane Company embarked on a small-scale test program to (1) investigate the ground surface environment which might result from various types of engines used to provide lift during the vertical mode of flight, (2) test various types of natural ground surface materials such as sand, gravel and sod,and (3) evaluate synthetic materials that might be used to cover the ground plane and prevent debris, such as rocks and dirt from flying into the air and being ingested into the engine inlet.

SCOPE OF PROGRAM

Figure 1 shows the scope of the program which included using small-scale nozzles with gas temperatures up to 3000°F and nozzle pressure ratios up to 3.0 to simulate the exhaust conditions commensurate with lifting devices such as lift fans, turbofans, turbojets and afterburning turbojets. Lift fans are large diameter fans driven by a shaft or tip turbine. Turbofans and turbojets are the conventional turbine engines.

With the exhaust directed perpendicular to the ground plane, measurements were made of surface dynamic pressures parallel to the ground plane and surface gas temperatures. Following this, natural ground surfaces such as sand, gravel and sod were tested to determine their compatibility with various power plant exhausts as well as ground cover materials such as asphalt, concrete, wet plywood, and various fiberglass and asbestos composite materials.

TEST APPARATUS

The impingement test apparatus is shown on Figure 2. The test rig was made up of a high-pressure air supply, an inter-burner for establishing gas temperatures up to 1500°F, and an afterburner for obtaining the higher gas temperatures in the 3000°F region. An instrumented flat plate with total pressure, static pressure and temperature probes, located along three axes, is shown as well as the various test nozzles. The test nozzles were approximately 2.5 inches in diameter except for the lift-fan nozzle which was 6 inches in diameter. Provisions were made to supply both hot and cold exhaust streams to the turbofan nozzle.

The air supply pipe was designed with a swivel joint so that the nozzle could be raised to the horizontal position, the test conditions established, and then the nozzle dropped down with the exhaust impinging on the test surface.

FLAT-PLATE DATA

Figure 3 presents the measured surface dynamic pressures. These were obtained by means of total and static pressure probes located on the surface of the plate. The total probes were located 0.1 inch above the plate and were out of the boundary layer. Looking at the chart on the left, we have surface dynamic pressure in pounds per square foot vs. distance laterally from the nozzle centerline in nozzle diameters. This chart is for a nozzle height of 1 diameter. Data for various types of nozzles are shown, and we see that in all cases the maximum surface dynamic pressure occurs on the plate about 1 nozzle diameter from the centerline and the dynamic pressure decreases rapidly as we move away from the nozzle centerline.

It is obvious that a turbojet engine with a nozzle pressure ratio of 3.0 produces surface dynamic pressures that are very high--on the order of 3000 psf. The turbofan is considerably lower and the lift fan is only about 500 psf. The surface Mach numbers varied from 0.4 for the lift fan to 1.3 for the turbojet. The chart on the right demonstrates how the maximum surface dynamic pressures vary as a function of nozzle height above the plate, and it is shown here that increasing nozzle height does not cause a significant reduction in the surface dynamic pressure. At a height of 5 nozzle diameters, the maximum surface dynamic pressure from a high specific thrust turbojet is 2500 psf.

Surface temperature data (Figure 4) follow a similar trend with the maximum gas temperatures occurring directly in line with the nozzle, the temperatures dropping off quite rapidly as we move away from the nozzle centerline as shown on the chart on the left. The curves shown are for an afterburning turbojet of 3000°F, a turbojet at 1500°F, and a turbofan at 1000°F. The chart on the right shows that the reduction of maximum surface gas temperature with nozzle height is very slight even at a height of 5 diameters. This is particularly significant to the airplane designer since he is concerned with the height of the nozzle above the ground so that the ground blast problem can be alleviated. No temperature data were obtained with the lift-fan nozzle because it was anticipated to handle only cold air. An ejector-type nozzle would have exhaust temperatures in the 300 to 400° range.

GROUND SURFACE TESTS

Following the flat-plate tests, a series of natural ground surfaces was tested. In Figure 5 movie frames are presented to show what happens to wet sand when subjected to a jet with a pressure ratio of 1.04 and a nozzle height of 3 diameters. This simulates the downwash from a propeller. After 12 seconds, a deep hole formed in the sand. With dry sand, an extremely low velocity or pressure ratio was required to blow it about.

One-inch diameter gravel was tested and was scattered about with the small-scale nozzles. Figure 6 presents some scenes from a simulated lift-fan test. The nozzle pressure ratio was 1.15, the nozzle height 1 diameter, and for this test the gravel was about 1/2-inch in diameter. Note how the gravel is blown upward.

Figure 7 presents a simulated lift-fan test with grass sod. After 60 seconds there was no effect on the sod. It is important to point out, however, that there are infinite varieties of sod, and factors such as the type of grass, the soil, root structure, etc., can influence the ability of sod to withstand dynamic pressure. We found that the Seattle-area, Puget Sound winter sod was extremely poor and disintegrated almost immediately. A loam-soil nursery sod that was very thick with a heavy root structure could withstand dynamic pressures up to 2000 psf, but the average sod would be limited to well below 1000 psf.

A test of common road-type asphalt is presented in Figure 8. The gas temperature was 400°F, and the nozzle pressure ratio was 1.25. This simulates an ejector nozzle exhaust stream. Note how the asphalt deteriorates. This is what one would expect since road asphalt melts at about 300°F.

Tests of concrete using a turbojet nozzle at 1500°F showed that concrete could withstand the environment except for the top 1/4-inch of finish cement. The upper photograph of Figure 9 shows concrete after 120 seconds of testing at 1500°F. The lower photograph shows a specimen of concrete subjected to an afterburner blast at 3000°F. After 30 seconds the concrete had eroded to a depth of about 1/2 inch. It is believed that the deterioration of concrete is caused by the moisture in the concrete turning to steam and the material failing due to internal pressure.

SYNTHETIC GROUND COVERS

The test program also encompassed the evaluation of synthetic materials that might be utilized to cover the ground surface, thus keeping flying debris to a minimum during a vertical takeoff or landing. Some of the materials tested are presented in Figures 10 through 13. Basically, there were two families of materials used, glass cloth and asbestos. Material coatings, resins, and manufacturing techniques were varied to obtain resistance to high temperatures and high erosion forces. Wire mesh was incorporated in some of the samples. Characteristics of the materials presented in Figures 10 through 13 are tabulated below:

Figure No.	Type of Material	Binder	Fabric	Estimated Raw Matls. Cost, Per Sq. Yard
10 and 11	Silicone rubber-coated glass cloth (2 ply)	Silicone rubber	Glass cloth	$9.00
10 and 11	Rubber-coated asbestos (1 ply)	Viton A-Hu	Asbestos	$12.00
10	Teflon-coated asbestos wire weave (1 ply)	Teflon	Asbestos inconel wire	$8.00
11	Silicone-coated "Fiberfax" plus wire (3 ply)	Silicone	Aluminum silicate fiber ("Fiberfax") plus wire	$135.00
12	Phenolic glass cloth board	Phenolic resin	Pieces of glass cloth	$78.00
12 and 13	Phenolic asbestos board board	Phenolic resin	Pieces of asbestos	$63.00
13	Phenolic glass cloth board	Phenolic resin	Refrasil	$147.00

The silicone rubber-coated glass cloth shown in Figure 10 was very satisfactory when subjected to a turbofan environment showing no deterioration after 120 seconds at 1000°F. The rubber-coated asbestos was also satisfactory. These materials are flexible and lightweight. The Teflon-coated asbestos-wire weave material tended to fray at the edges. This was caused by the exhaust gas penetrating the material, flowing along the plate, and damaging the edges.

Figure 11 presents two of the same materials, silicone-coated glass cloth and rubber-coated asbestos--subjected to the environment of a high specific output turbojet (nozzle pressure ratio of 3.0 and temperature of 1500°F). After 30 seconds these materials were badly damaged. A third material composed of "Fiberfax", silicone and wire was also badly damaged.

In order to achieve a satisfactory material to withstand the severe environment of a turbojet, it was necessary to fabricate a board-type material composed of phenolic glass cloth or phenolic asbestos board as shown in Figure 12. These are rigid materials about 1/4 inch in thickness and are quite costly. (See above tabulation). After exposure to a turbojet exhaust of 1500°F for 120 seconds, only a discoloration of the material was apparent.

These same types of materials were found to be satisfactory with afterburning nozzles. Figure 13 shows no damage after 30 seconds at 3000°F.

SUMMARY

The results of the test program may be summarized by dividing the various ground surfaces into two categories: (1) those that are primarily susceptible to surface dynamic pressures and (2) those that are primarily susceptible to temperature or combined temperature and dynamic pressure.

The upper chart on Figure 14 presents those surfaces that are affected primarily by dynamic pressure. Sand is blown about at a very low pressure, gravel can withstand a slightly higher pressure, and sod is limited to about 2000 psf. However, this was the special type of nursery sod and the average sod will disintegrate at pressures below 1000 psf. Superimposed on this chart are the dynamic pressure ranges for the various lifting devices. It appears that only a lift-fan airplane could operate from a sod field, and none of the lift systems would be capable of operating from a sand or gravel surface.

The lower chart on Figure 14 presents the limitations of materials that are primarily temperature sensitive. The road asphalt melted at 300°F, but it is believed that it is possible to obtain asphalt which can withstand temperatures up to about 600°F. The flexible silicone-coated glass cloth material was satisfactory up to 1300°F. Concrete was limited to 1400°F, and the phenolic glass cloth or asbestos board materials can withstand 3000°F.

CONCLUSION

The VTOL exhaust environment is found to be extremely severe in the case of the turbojet, both afterburning and non-afterburning. The turbofan engine is considerably more favorable from a ground blast standpoint, and the lift-fan or ejector system is even more desirable. All of these lifting systems will require some type of site preparation to create a satisfactory surface for airplane operation. The concept of VTOL jet aircraft operating with any degree of success from an unprepared site is of extreme doubt.

The ground cover materials which appear to be suitable from the standpoint of exhaust ground environment for the respective propulsion systems are as follows: (See Figure 15)

(1) With a lift-fan or ejector nozzle, suitable materials are sod, a lightweight membrane, or asphalt (marginal).

(2) With a turbofan engine, steel, concrete, or a flexible membrane such as silicone-coated glass cloth or rubber-coated asbestos are suitable.

(3) With a turbojet engine, a steel mat or platform will be required or a rigid board material such as resin and glass cloth or resin and asbestos. Concrete will be marginal.

(4) An afterburning turbojet will require a steel mat or platform, or the rigid board materials described above.

PROGRAM SCOPE

USING SMALL-SCALE NOZZLES WITH HOT GAS
- VERTICAL IMPINGEMENT

SIMULATING LIFT FANS
- TURBO FANS
- TURBO-JETS
- A/B TURBO-JETS

MEASURE SURFACE DYNAMIC PRESSURES
- SURFACE TEMPERATURES

EVALUATE SUITABILITY OF NATURAL SURFACES
- SYNTHETIC GROUND COVERS

284874-16

Figure 1

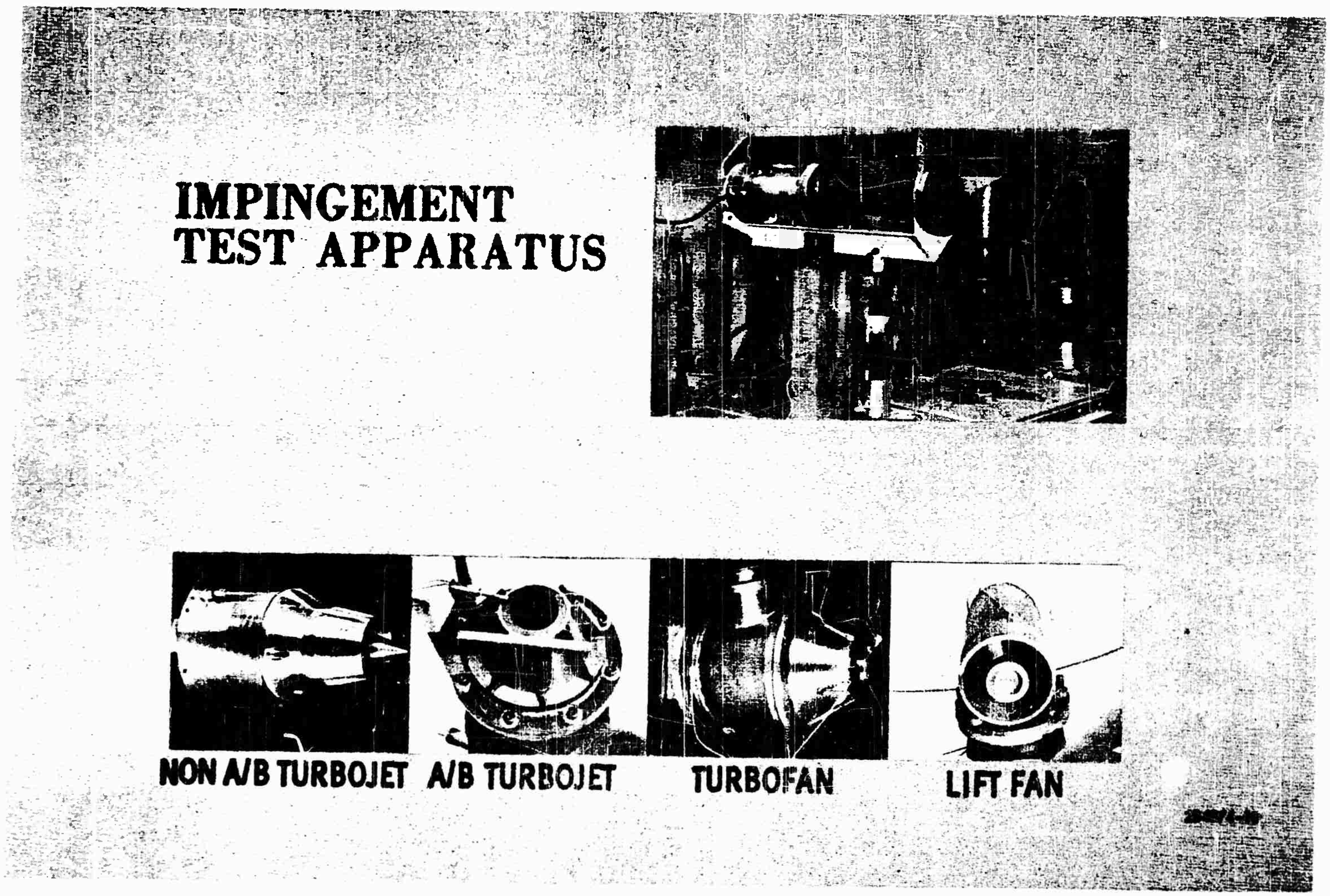

IMPINGEMENT
TEST APPARATUS
NON A/B TURBOJET
A/B TURBOJET
TURBOFAN
LIFT FAN

Figure 2

72

SURFACE DYNAMIC PRESSURE DATA

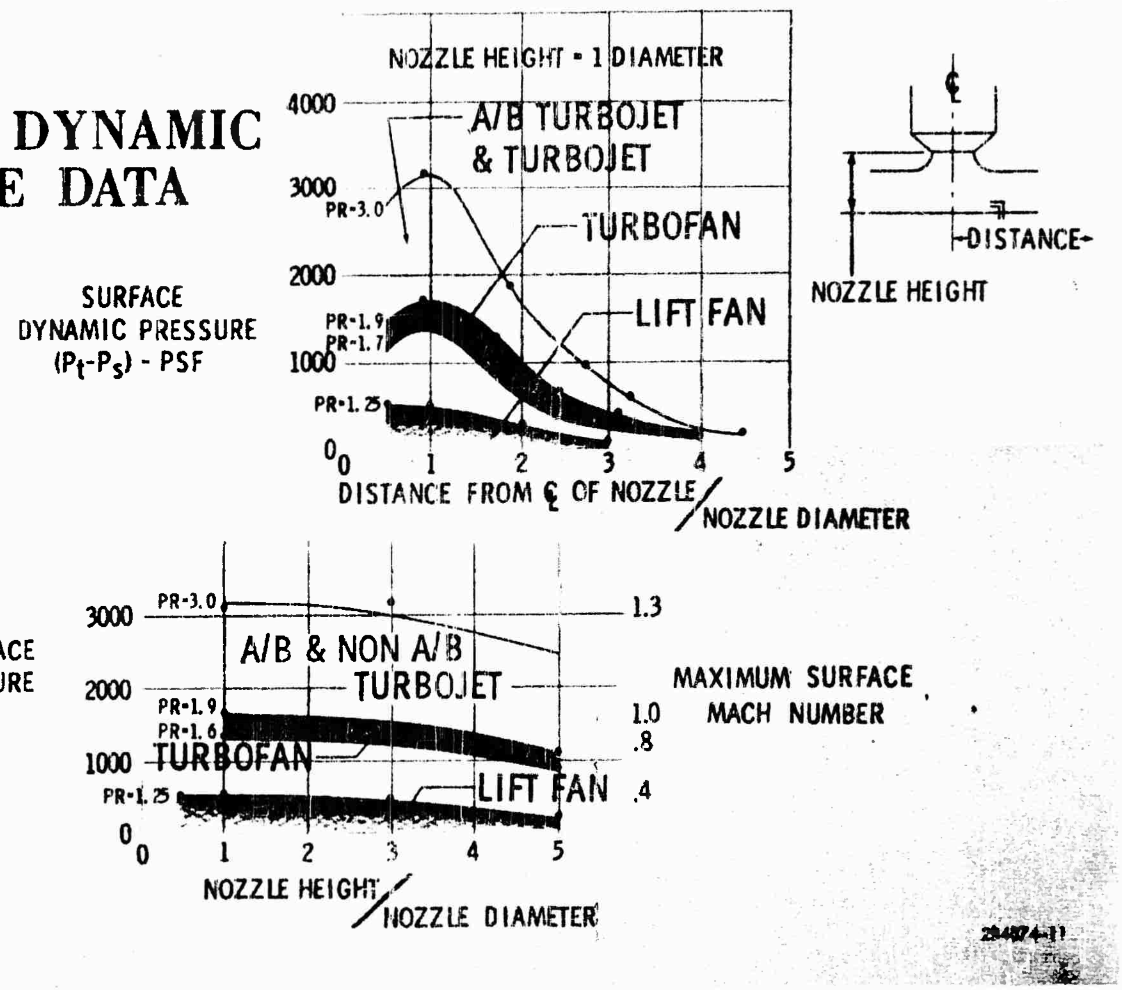


Figure 3

7 2

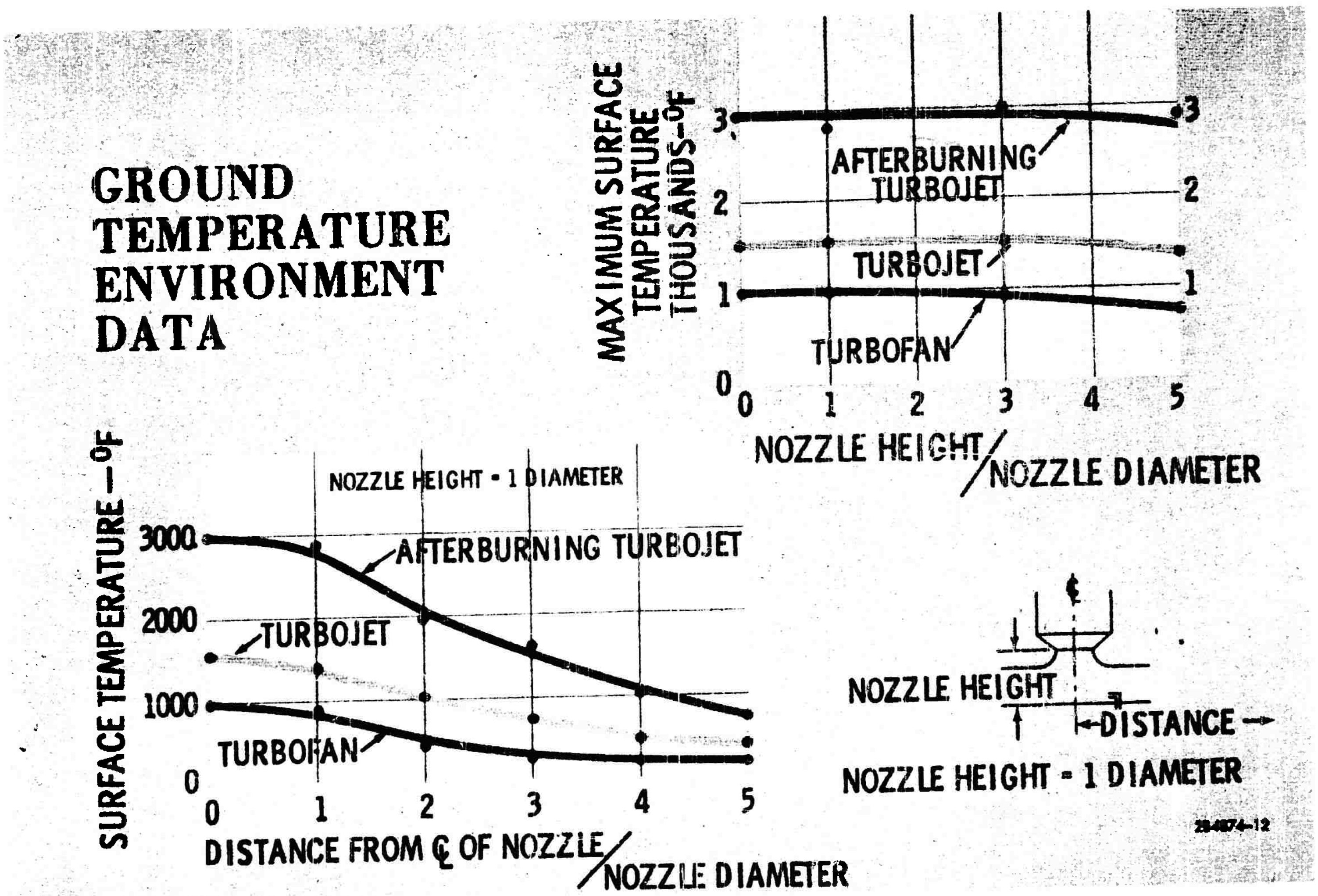
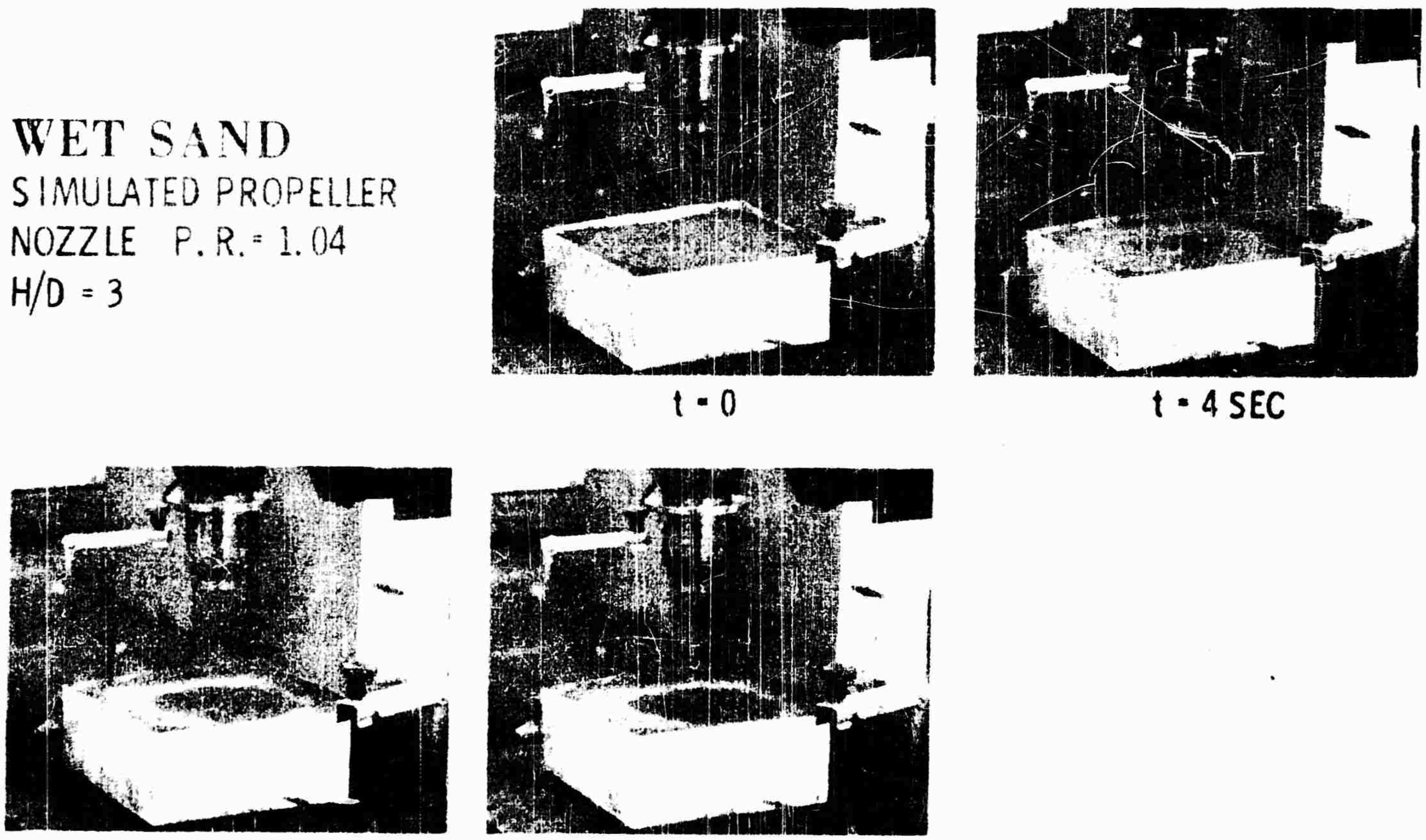

GROUND TEMPERATURE ENVIRONMENT DATA
MAXIMUM SURFACE TEMPERATURE THOUSANDS—°F
AFTERBURNING TURBOJET
TURBOJET
TURBOFAN
0 1 2 3
0 1 2 3 4 5
NOZZLE HEIGHT/NOZZLE DIAMETER
SURFACE TEMPERATURE —°F
NOZZLE HEIGHT = 1 DIAMETER
3000 2000 1000 0
AFTERBURNING TURBOJET
TURBOJET
TURBOFAN
0 1 2 3 4 5
DISTANCE FROM ℄ OF NOZZLE/NOZZLE DIAMETER
℄
NOZZLE HEIGHT
DISTANCE
NOZZLE HEIGHT = 1 DIAMETER
2B4874-12

Figure 4

72

WET SAND
SIMULATED PROPELLER
NOZZLE P.R. = 1.04
H/D = 3



t = 0 t = 4 SEC

t = 8 SEC t = 12 SEC

2B4874-5

Figure 5

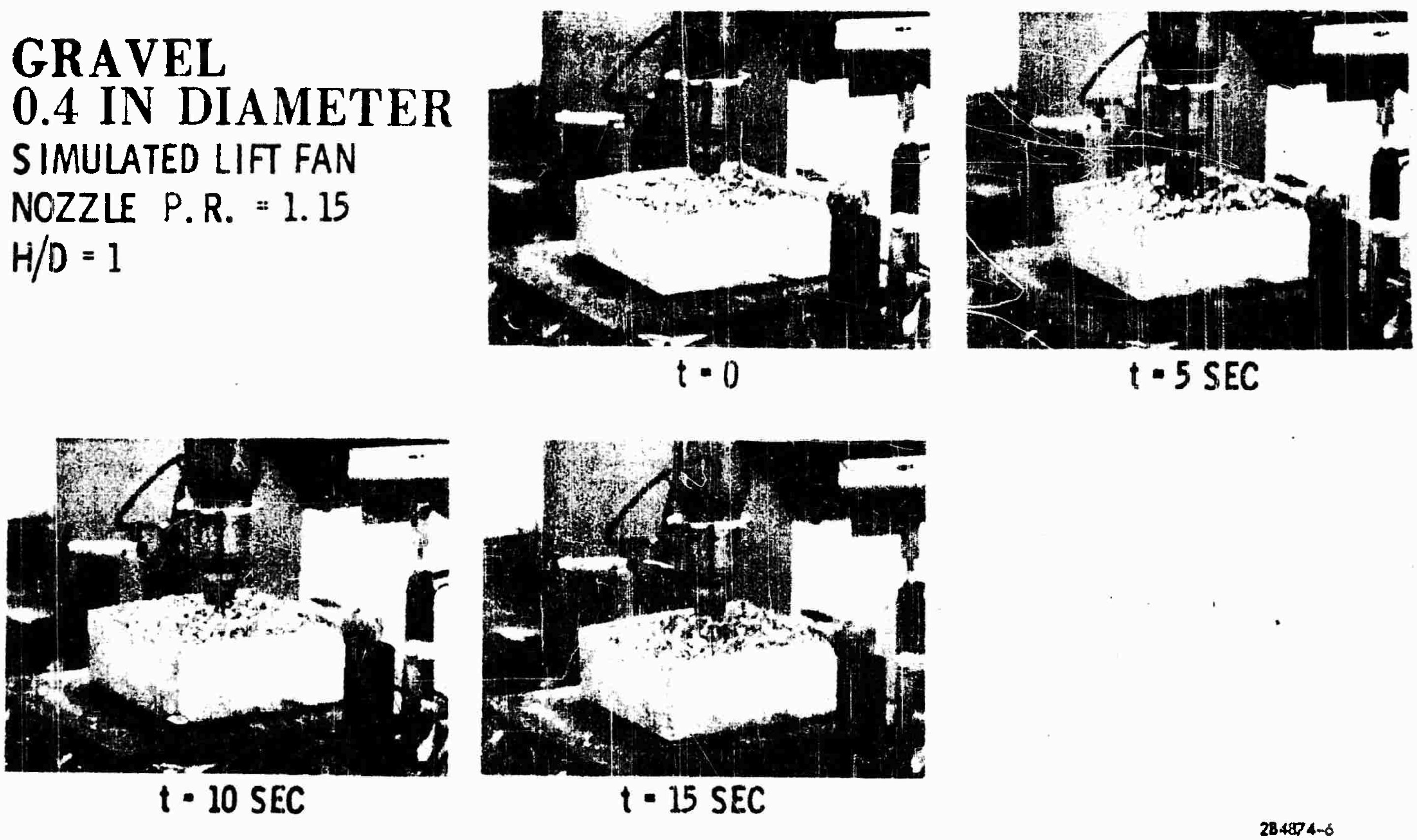

GRAVEL
0.4 IN DIAMETER
SIMULATED LIFT FAN
NOZZLE P.R. = 1.15
H/D = 1
t = 0
t = 5 SEC
t = 10 SEC
t = 15 SEC
2B4874-6

Figure 6

WET CLAY SOD

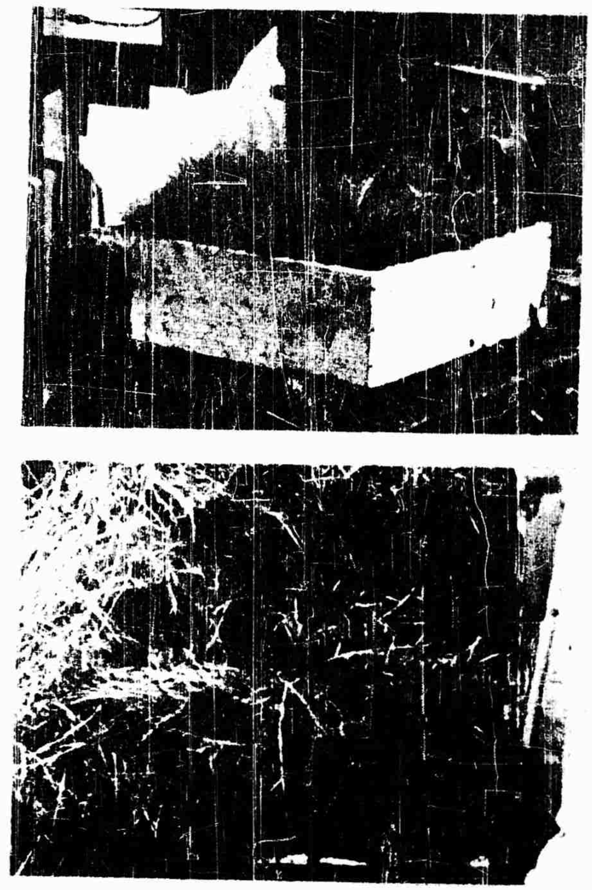
SIMULATED LIFT FAN

NOZZLE P.R. = 1.25

H/D = 1.0

t = 0

t = 60 SEC



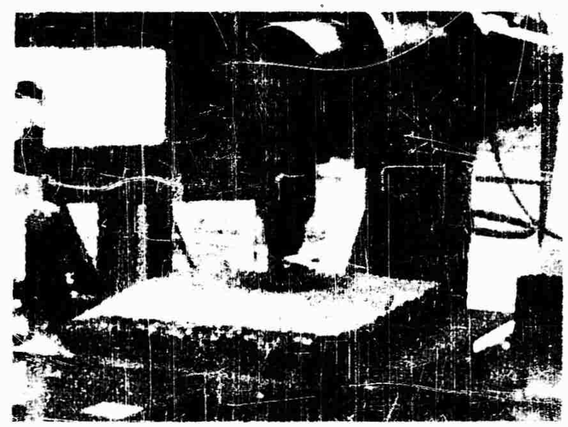
28-874-7

Figure 7

ASPHALT ROAD TYPE

NOZZLE P.R. = 1.25
NOZZLE TEMP = 400^0 F
H/D = 1

T = 10 SEC



T = 30 SEC
0.4-IN. HOLE IN 30 SEC

2B4874-8

Figure 8

CONCRETE

NOZZLE P.R. = 3.0
H/D = 1

NOZZLE TEMP. = $1500^{\circ}F$
TIME = 120 SEC

NOZZLE TEMP = $3000\ ^{\circ}F$
TIME = 30 SEC

284874-9

Figure 9

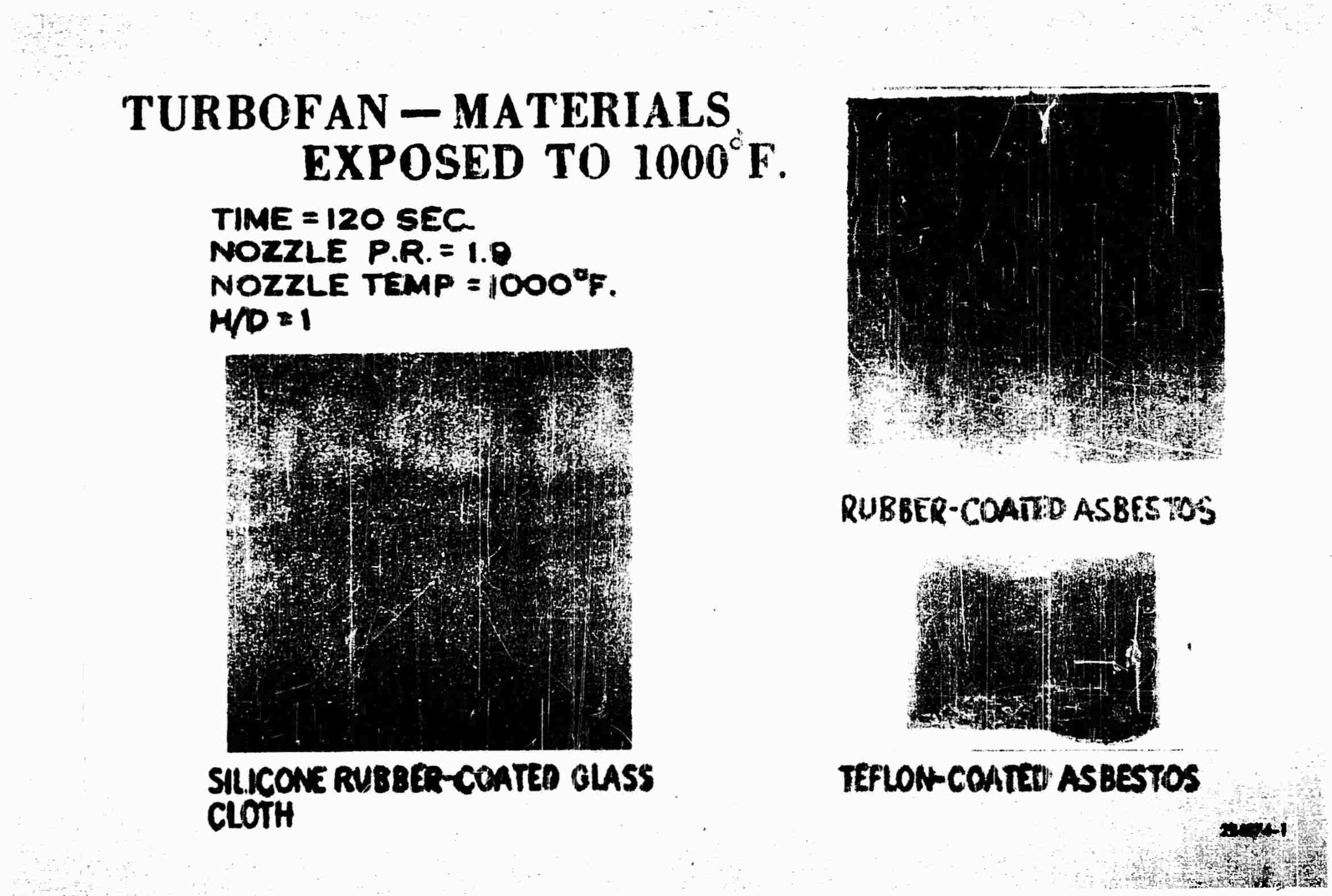

TURBOFAN — MATERIALS
EXPOSED TO 1000°F.
TIME = 120 SEC.
NOZZLE P.R. = 1.9
NOZZLE TEMP = 1000°F.
H/D = 1
SILICONE RUBBER-COATED GLASS CLOTH
RUBBER-COATED ASBESTOS
TEFLON-COATED ASBESTOS

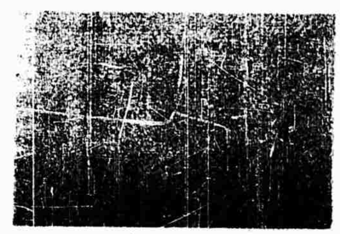
Figure 10

TURBOJET — MATERIALS EXPOSED TO 1500°F

TIME = 30 SEC
NOZZLE P R. = 3.0
NOZZLE TEMP. = 1500°F

SILICONE RUBBER-COATED GLASS CLOTH

RUBBER-COATED ASBESTOS



FIBERFAX-SILICONE-WIRE

284874-2

Figure 11

72

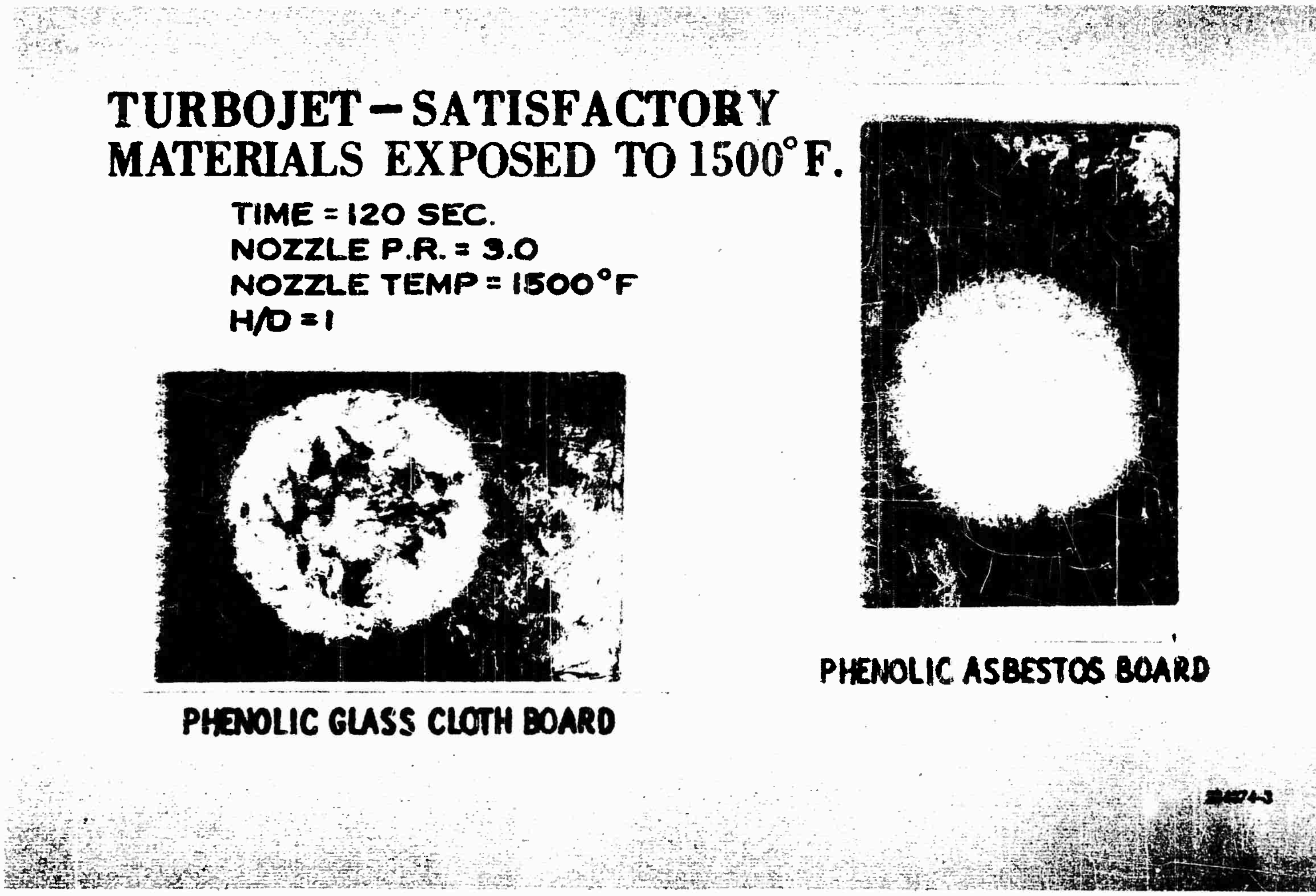

TURBOJET – SATISFACTORY
MATERIALS EXPOSED TO 1500°F.
TIME = 120 SEC.
NOZZLE P.R. = 3.0
NOZZLE TEMP = 1500°F
H/D = 1
PHENOLIC GLASS CLOTH BOARD
PHENOLIC ASBESTOS BOARD

Figure 12

AFTERBURNING TURBOJET MATERIALS EXPOSED TO 3000°F.

TIME = 30 SEC
NOZZLE P.R. = 3.0
NOZZLE TEMP = 3000°F.
H/D = 1

PHENOLIC GLASS CLOTH BOARD

PHENOLIC ASBESTOS BOARD

Figure 13

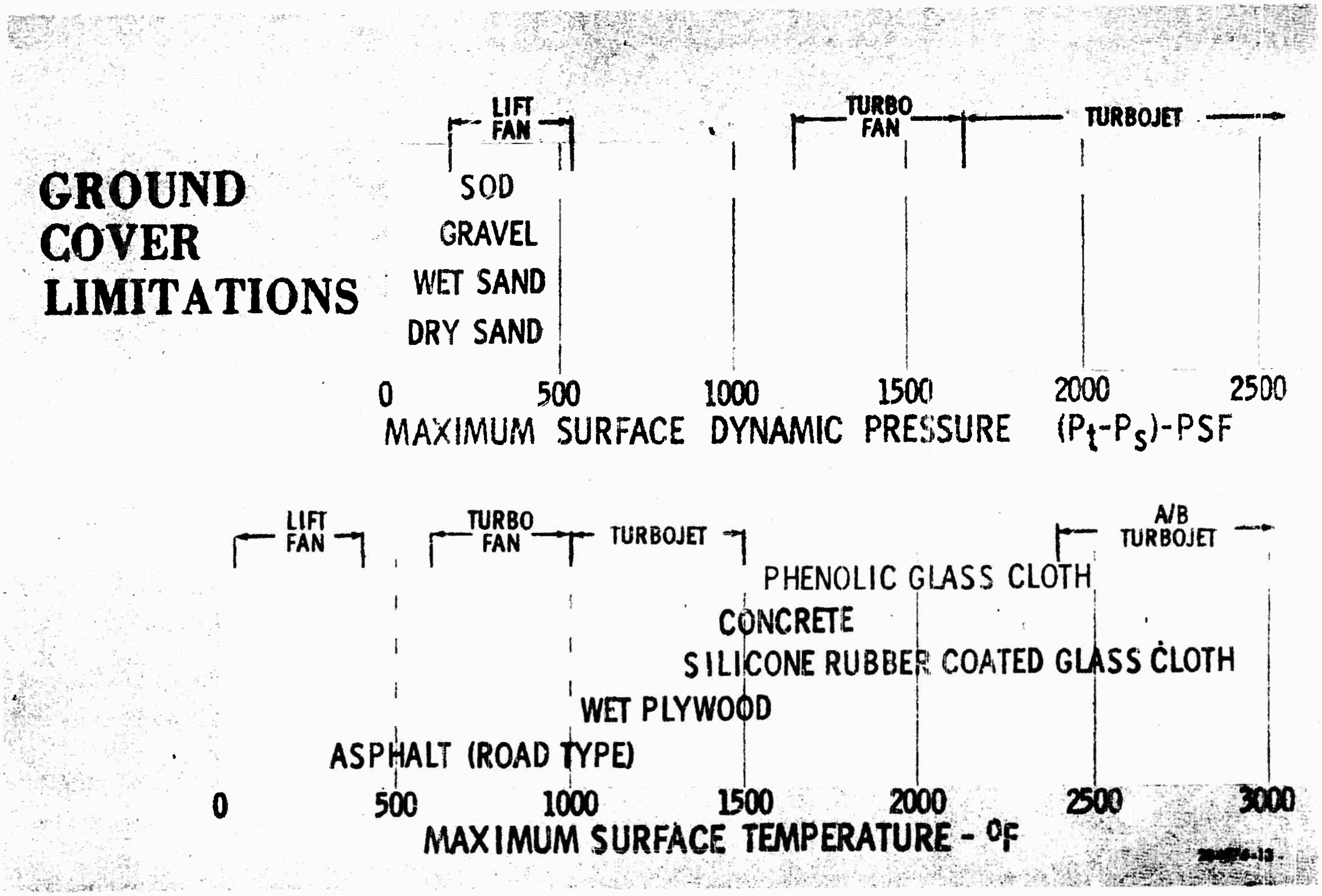

GROUND
COVER
LIMITATIONS
LIFT FAN
TURBO FAN
TURBOJET
SOD
GRAVEL
WET SAND
DRY SAND
0
500
1000
1500
2000
2500
MAXIMUM SURFACE DYNAMIC PRESSURE (P_t-P_s)-PSF
LIFT FAN
TURBO FAN
TURBOJET
A/B TURBOJET
PHENOLIC GLASS CLOTH
CONCRETE
SILICONE RUBBER COATED GLASS CLOTH
WET PLYWOOD
ASPHALT (ROAD TYPE)
0
500
1000
1500
2000
2500
3000
MAXIMUM SURFACE TEMPERATURE - °F

Figure 14

SUITABLE GROUND COVER MATERIALS

- LIFT FAN & EJECTOR
  - SOD
  - MEMBRANE (LIGHT WEIGHT & FLEXIBLE)
  - ASPHALT (MARGINAL)
- TURBO-FAN
  - CONCRETE
  - MEMBRANE (LIGHT WEIGHT & FLEXIBLE
    - SILICONE RUBBER COATED GLASS CLOTH
    - SYNTHETIC RUBBER COATED ASBESTOS ETC.
- TURBO-JET
  - STEEL MAT OR PLATFORM
  - RIGID COVERS
    - RESIN & GLASS CLOTH (1/4" THICK)
    - RESIN & ASBESTOS
  - CONCRETE (MARGINAL)
- A/B TURBO-JET
  - STEEL MAT OR PLATFORM
  - RIGID COVERS
    - RESIN & GLASS CLOTH
    - RESIN & ASBESTOS

2B4874-14

Figure 15

PAPER NO. 14

V/STOL IMPINGEMENT TESTS ON DUCTED PROPELLERS AND TURBOJETS

by

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(Text of speech based on a paper entitled "Flow Phenomena Experienced With VTOL Aircraft in Ground Proximity", presented at the AGARD V/STOL Symposium, Paris, France, June 1960. Copies of the paper are available from Bell Aerosystems Company.)